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AIRCRAFT BATTERY STATE OF CHARGE AND CHARGE CONTROL

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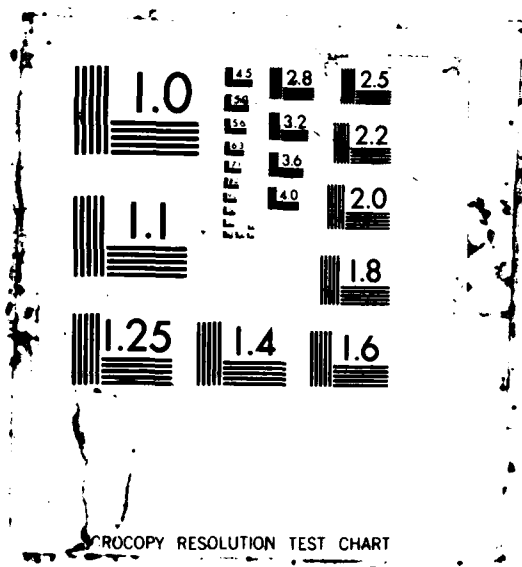
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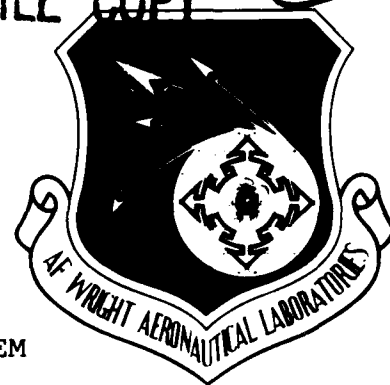
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AIRCRAFT BATTERY STATE OF CHARGE AND CHARGE CONTROL SYSTEM

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April 1987

Interim Report for Period July 1985 - June 1986

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This Interim Report describes work done by Energy Research Corporation (ERC) in developing an aircraft battery state-of-charge indicator and charge control system. The basis for this system, developed by ERC, is a nickel-oxygen (NiO ₂) "pilot" cell (0.374 Ah). This pilot cell is cycled in tandem with a nickel-cadmium battery. The oxygen pressure of the pilot cell is used to determine and control the state-of-charge of the nickel-cadmium battery. Nickel-cadmium batteries from different manufacturers were cycled using this pilot cell charge indication and control system. The performance of the pilot cell and a nickel-cadmium battery as a function of temperature were separately determined. <i>(Keywords)</i>					
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1.0 INTRODUCTION

The start date for contract No. F33615-84-C-2435, "Aircraft Battery State of Charge and Charge Control System" was July 1, 1984.

Efforts during the first year were devoted to characterization of Ni-O₂ cell. In this second year, commercial aircraft batteries were tested as integrated systems at the brass board level.

Detailed technical data is regularly being submitted to Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory, Wright-Patterson Air Force Base through monthly letter reports. This second interim report summarizes the work performed during the second year of the contract, July 1985 to June 1986.

2.0 PROGRAM STATUS OVERVIEW

Work commenced in the first year in obtaining data on the baseline characteristics of the Ni-O₂ cell was continued during the second year. Investigations of the effects of temperature on cell performance were completed between 0°F and 140°F. Similar characterization was also performed with a 10-cell (Marathon Corp.) aircraft battery. Ni-O₂ cells fabricated with sintered nickel electrodes used in commercial aircraft batteries were also characterized.

Life cycle tests of Ni-O₂ cells made with ERC roll-bonded and commercial sintered electrodes are being continued. Test results have demonstrated life capability of nearly 2000 cycles over a time period of 20 months. This confirms that the life of the Ni-O₂ cells exceeds by a considerable margin the expected life of nickel cadmium batteries and is well qualified to monitor the state of charge of the main battery.

During this period an investigation of performance characteristics was carried out at temperatures other than ambient. Ni-O₂ cells were tested between 0°F and 140°F. In addition, a 10-cell Marathon aircraft battery was also tested at 140°F.

Using an electronic tracking cycler, designed and built in house, a commercial aircraft battery (SAFT) was cycled in tandem with a Ni-O₂ cell to evaluate system life and stability. Including open circuit stand over 500 charge-discharge cycles were carried out before stopping the tests due to reduced capacity of the aircraft battery. Despite minor fluctuations due to variations in room temperature, reliable tracking characteristics were demonstrated during the 7-month test run.

A second cyclor was built and an aircraft battery manufactured by Marathon was tested for tandem operation. The tests were carried out both at ambient and at other constant temperatures. Tests at constant temperature showed superior tracking accuracy by eliminating variations in pressure of the Ni-O₂ cell due to temperature excursions.

Another aircraft battery was purchased from a third manufacturer (GE) and characterized for performance. This will also be tested in tandem with a compatible Ni-O₂ cell.

Efforts during the final phase of the program will be directed towards system evaluation on tandem operation at ambient and cold temperatures. A fourth aircraft battery to be supplied by the Government will also be tested.

Based on this R & D effort, a technical presentation, "Battery State of Charge and Charge Control System", was given at the Electrochemical Society Conference, November 1985.

3.0 EXPERIMENTAL RESULTS

3.1 Ni-O₂ Cell Design

The nickel-oxygen test cells employed a three-electrode configuration utilizing one electrode for oxygen evolution and a different electrode for oxygen consumption. This concept divides the functions of charge and discharge and eliminates problems encountered in conventional two-electrode systems, in which catalysts that function well during oxygen consumption tend to oxidize or dissolve when subjected to evolution.

The normal specifications for the nickel electrodes are as follows:

Electrode Size	1.26 x 1.00 x .070 inch
Active Material	2.53 gms
Theoretical Capacity	0.440 Ah
Normal Capacity	0.374 Ah

Depending on the active material content, the area of the electrode is varied to obtain the required capacity. The cell can be designed to any capacity as long as the current is maintained proportionally.

3.2 Ni-O₂ Cell Tests

Using the three-electrode concept, the nickel electrode of the pilot cell is charged against the platinum gas electrode and discharged against the nickel screen. The potentials and pressure are monitored during the tests.

The electrodes are first housed in a test fixture and fully charged, the end of charge being indicated by the leveling out of the pressure profile. The cell is then discharged to 100% depth and the delivered capacity calculated. The procedure is repeated until the nickel electrode is stabilized

and reproducible results are obtained. This procedure qualifies the system, after which the electrode assembly is removed from the test fixture and assembled in a stainless steel can. Ziegler seals and welding of the cover ensure a leak-proof construction; then a pressure gauge is screwed on top. The cell is now ready to undergo characterization tests.

3.3 Life Cycle Tests

Life cycle tests which were begun in the first year were continued. In addition, cells were fabricated with sintered nickel plates from commercial aircraft batteries; these cells were also characterized and subjected to life cycle tests. Some of the tests were completed with the remaining ones continued into the third year. Test results of the cells are summarized below:

Cell No. 21: This cell was built using a sintered nickel electrode from commercial aircraft battery manufactured by SAFT. Life cycle tests were started in November 1984 and terminated in June 1986 when the cell failed. Cell voltages (nickel vs. platinum during charge, nickel vs. screen during discharge) and pressure were monitored at regular intervals. After about 450 cycles the polarization during discharge started to increase and stabilized at -2.0 volts after 600 cycles. This high value of polarization did not affect the relationship between cell pressure and the state of charge of the nickel electrode. The cell continued to exhibit the same characteristics - increased polarization towards end of discharge, levelling of pressure towards the end of charge and a linear relationship between state of charge and cell pressure - for 1,900 cycles.

During Cycle No. 1919, a marked change in the voltage profile was noticed; the rapid increase in voltage towards the end of discharge did not occur. In addition, the change in pressure during charge and discharge had dropped to 8 psig from a norm of 20. This indicates that the cell had lost its activity and ability to perform as required. Tests were continued for another 100 cycles to confirm that the cell's loss in activity was irreversible. This was found to be true and the tests were terminated. The changes in the voltage profile during discharge are apparent from Figures 1 and 2. Figure 3 shows the corresponding changes in pressure profile.

Representative data of the performance characteristics of Cell No. 21 are shown in Figures 4 through 11.

After terminating the tests, a failure analysis of the cell was performed. It should be pointed out that these are the longest life time tests performed on a single nickel oxygen cell. The cell was cycled over 2,000 times and including shutdown times, the cell was on test for 20 months.

The cell was carefully cut open and no defects such as dryout, shedding of nickel or corrosion were noticeable. It appears that failure was caused by loss in electrochemical activity of the nickel electrode.

The nickel electrode was carefully removed and SCM photographs were taken. For purposes of comparison, photographs of a fresh electrode were taken at the same magnifications. These are shown in Figures 12 and 13. It appears that the particles exhibited low density to

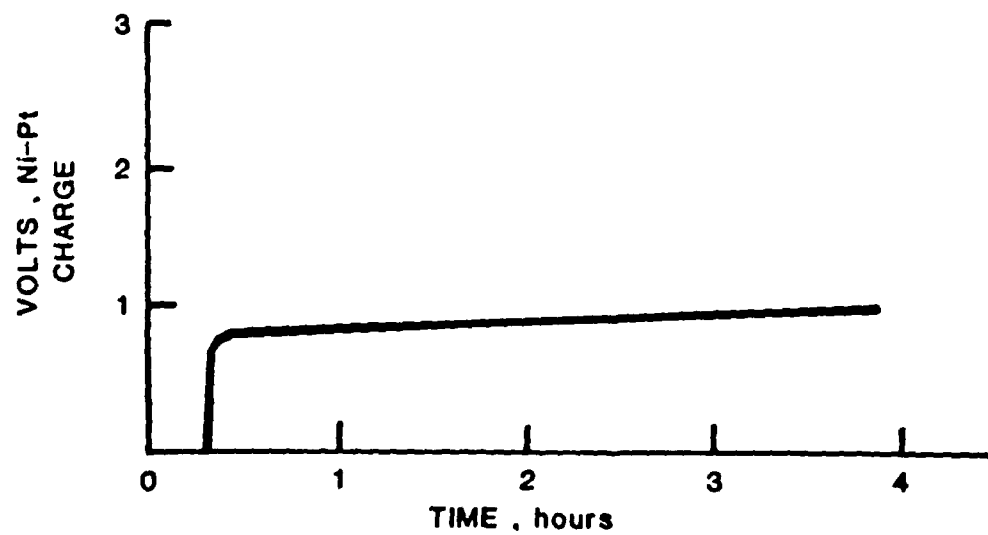
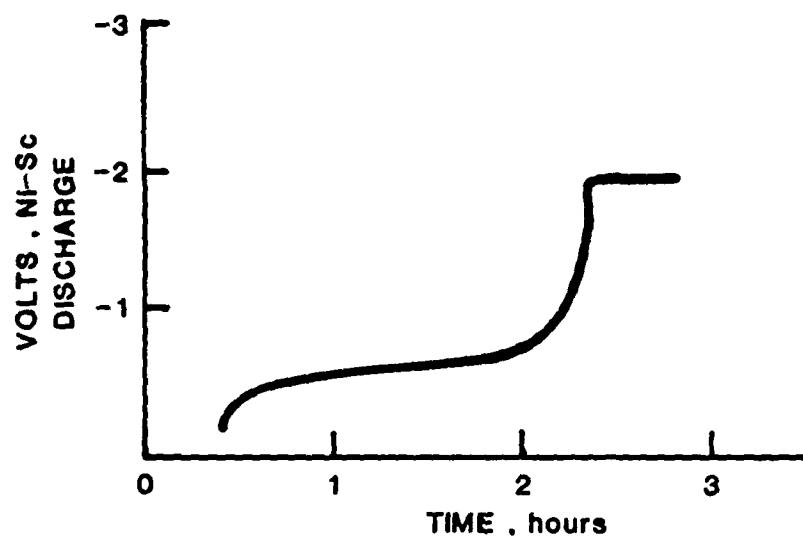


FIGURE 1 VOLTAGE PROFILE CELL 21 - CYCLE 1766

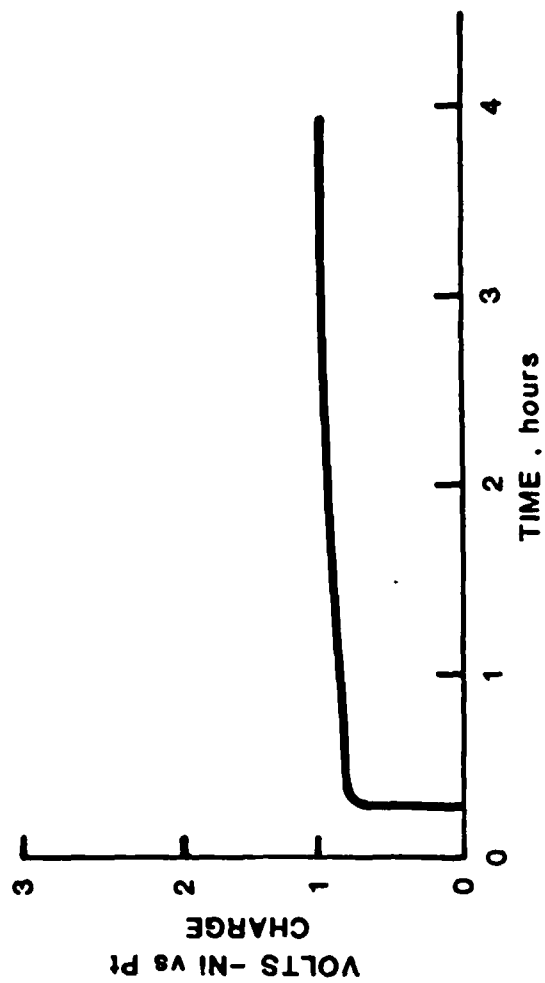
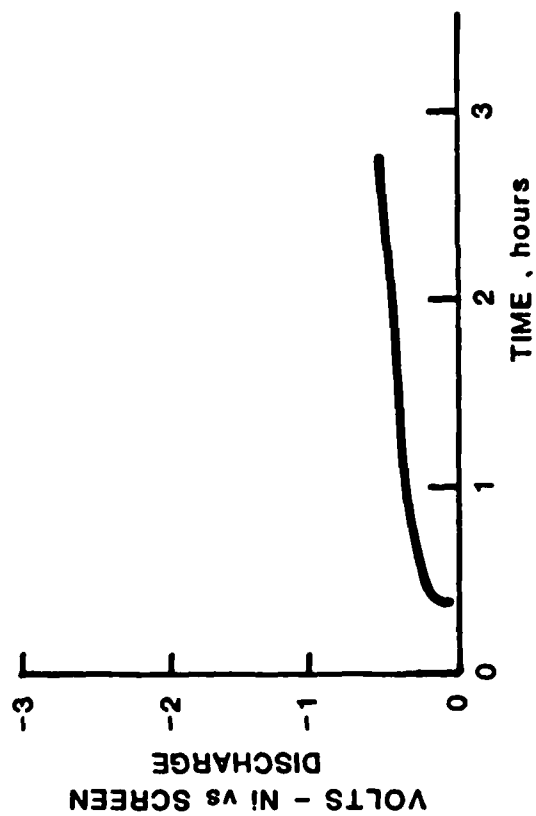


FIGURE 2 VOLTAGE PROFILE CELL 21 - CYCLE 1919

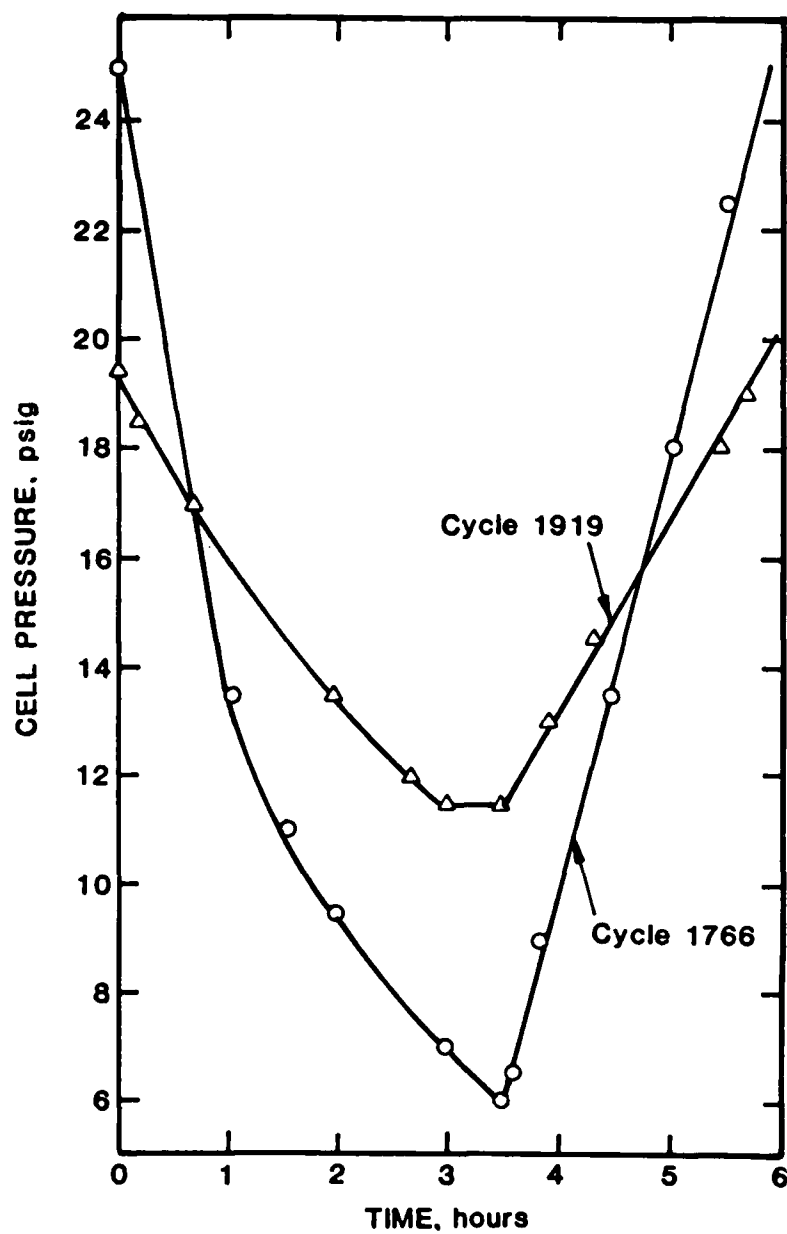


FIGURE 3: COMPARISON OF PRESSURE PROFILES-CELL #21

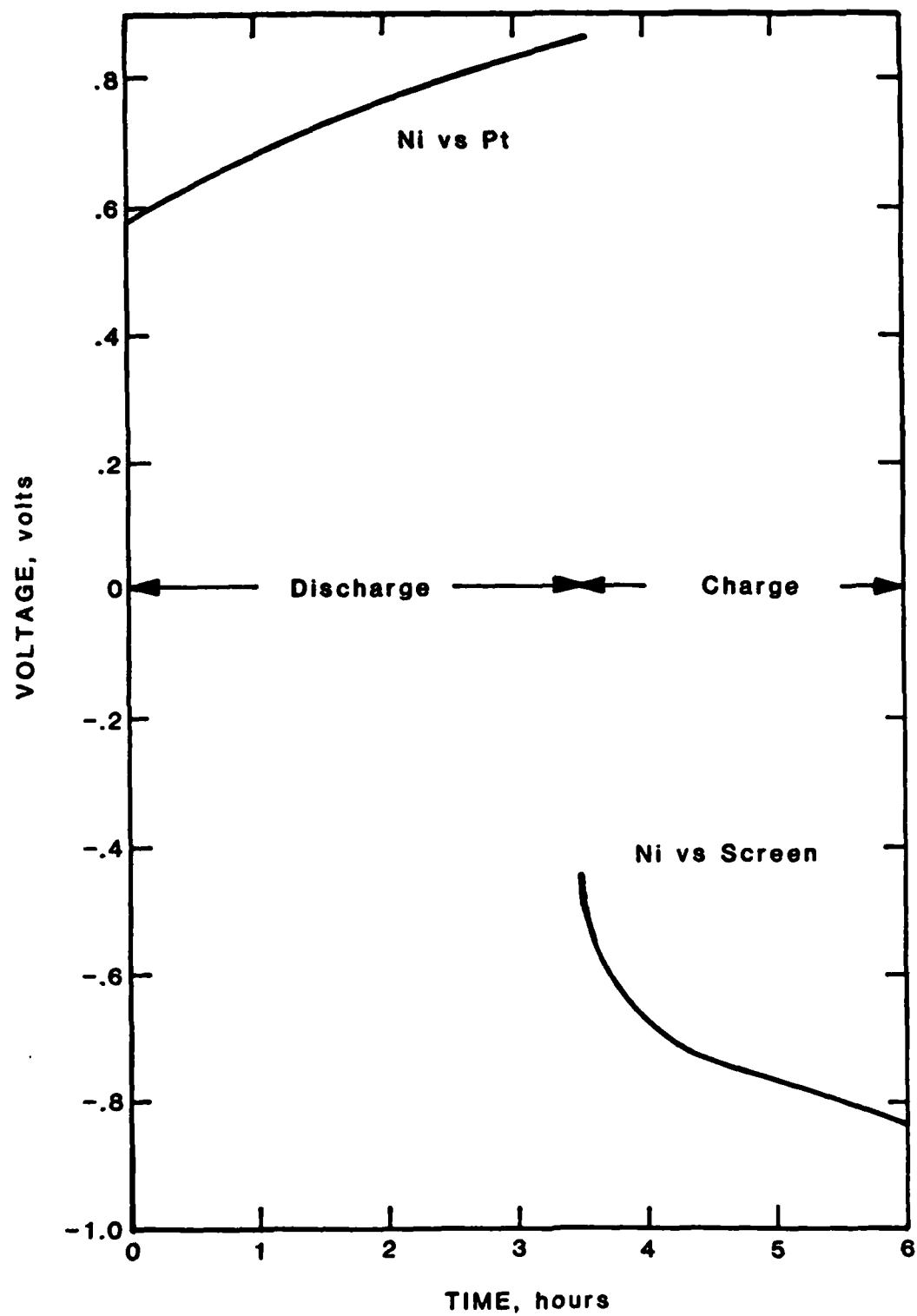


FIGURE 4: VOLTAGE PROFILE-CELL #21, CYCLE #100

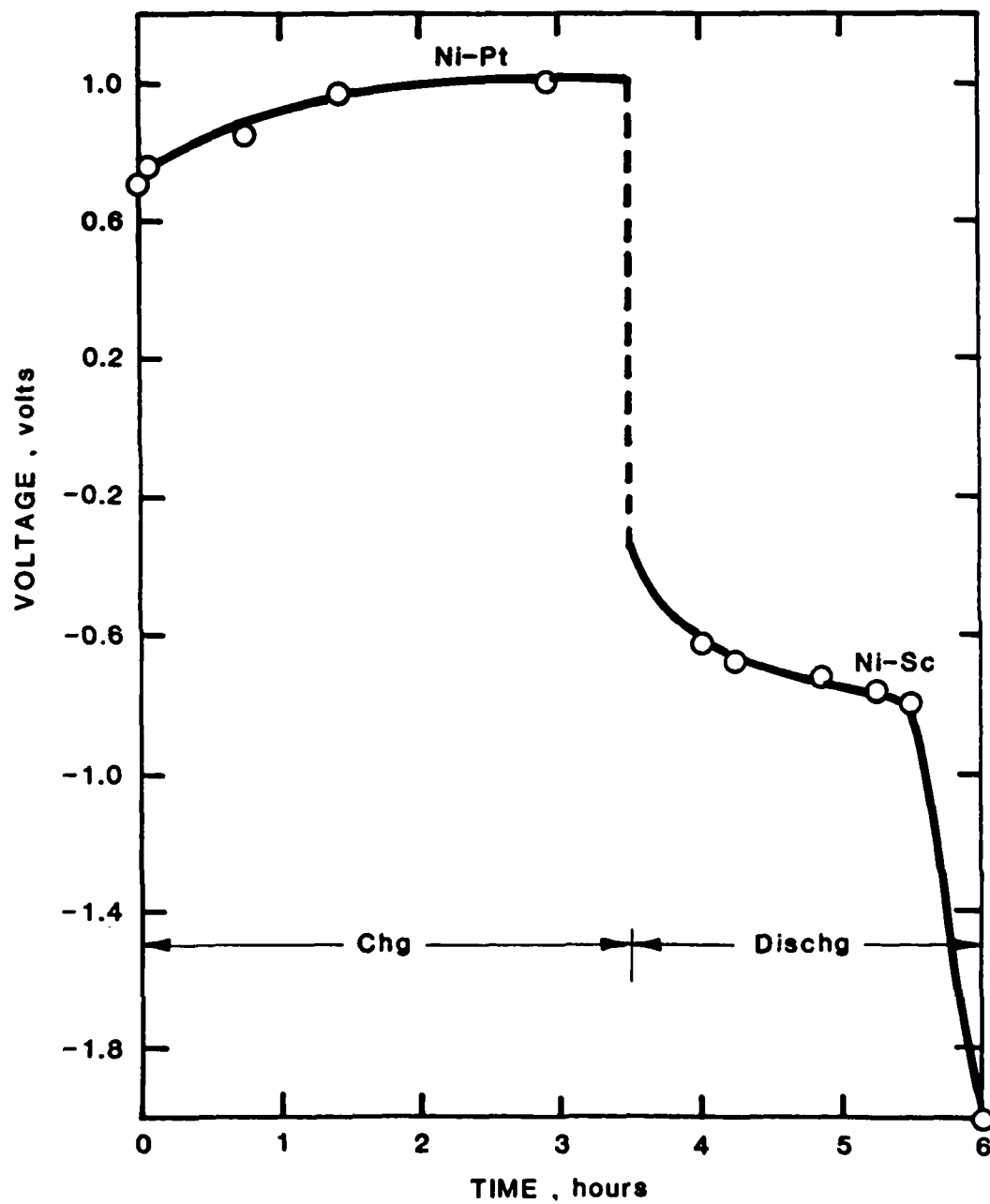


FIGURE 5 VOLTAGE PROFILE - CELL NO. 21, CYCLE NO. 562

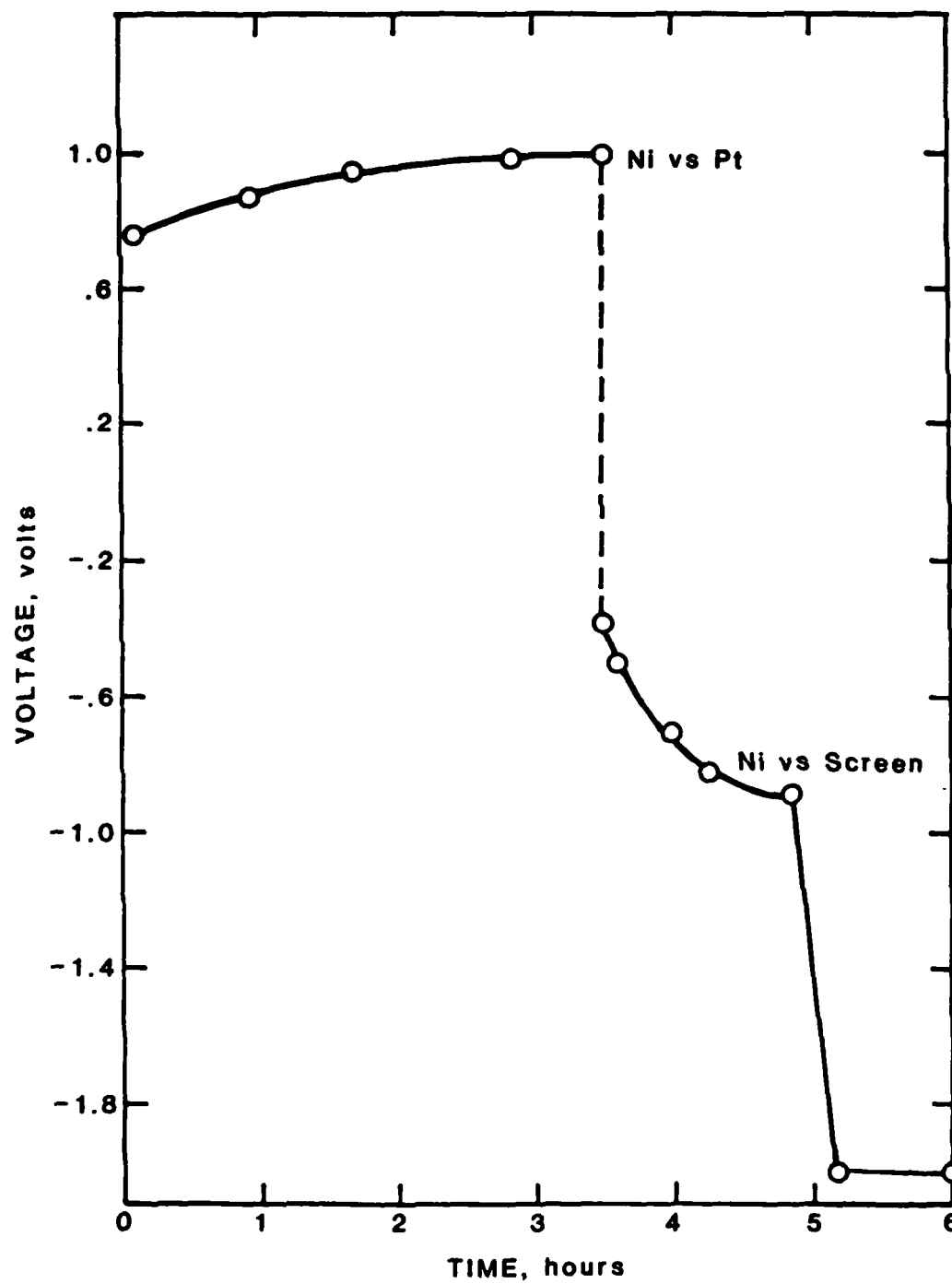


FIGURE 6: VOLTAGE PROFILE-CELL #21, CELL 1060

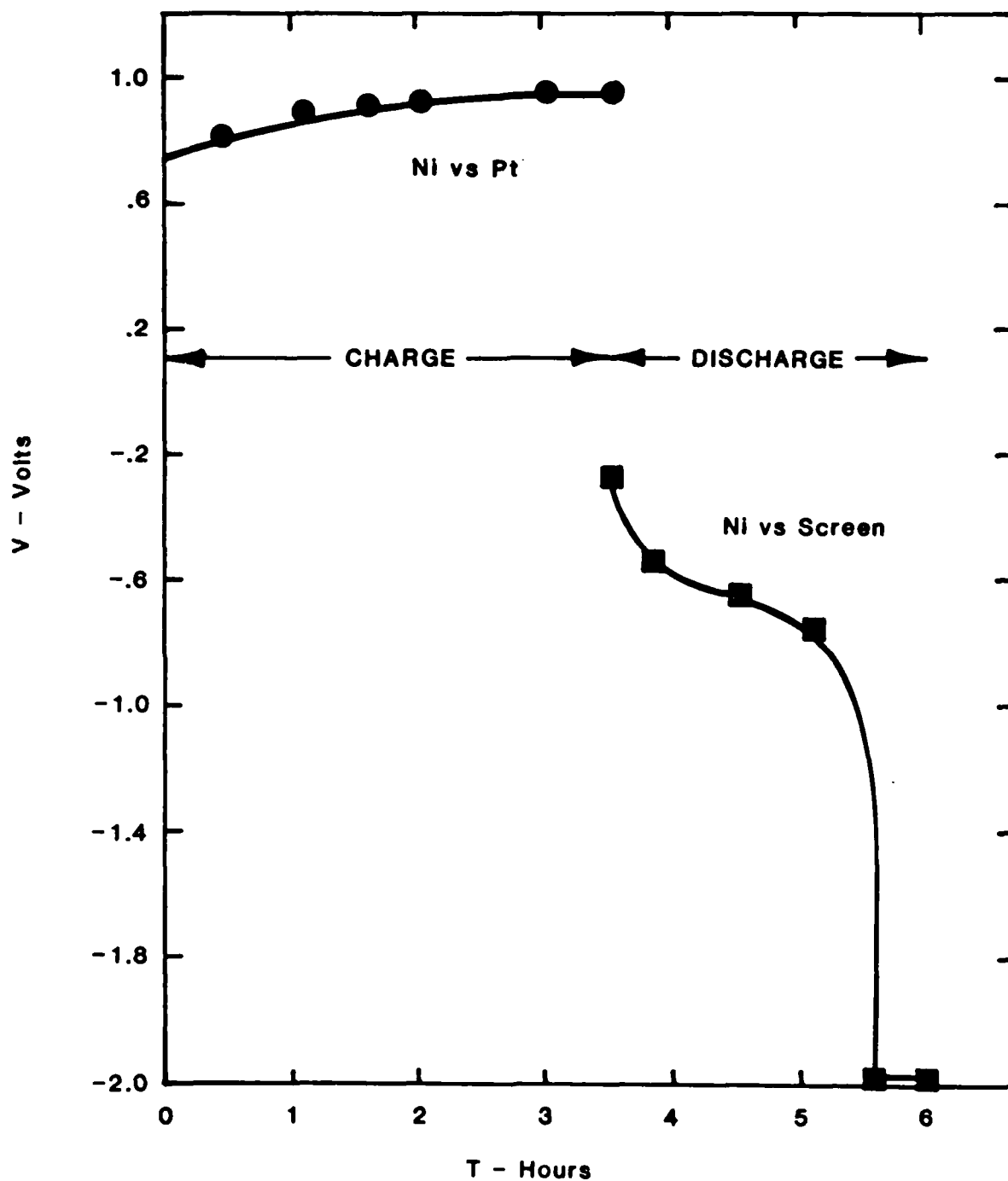


Fig. 7 Voltage Profile -Cell 21, Cycle 1764

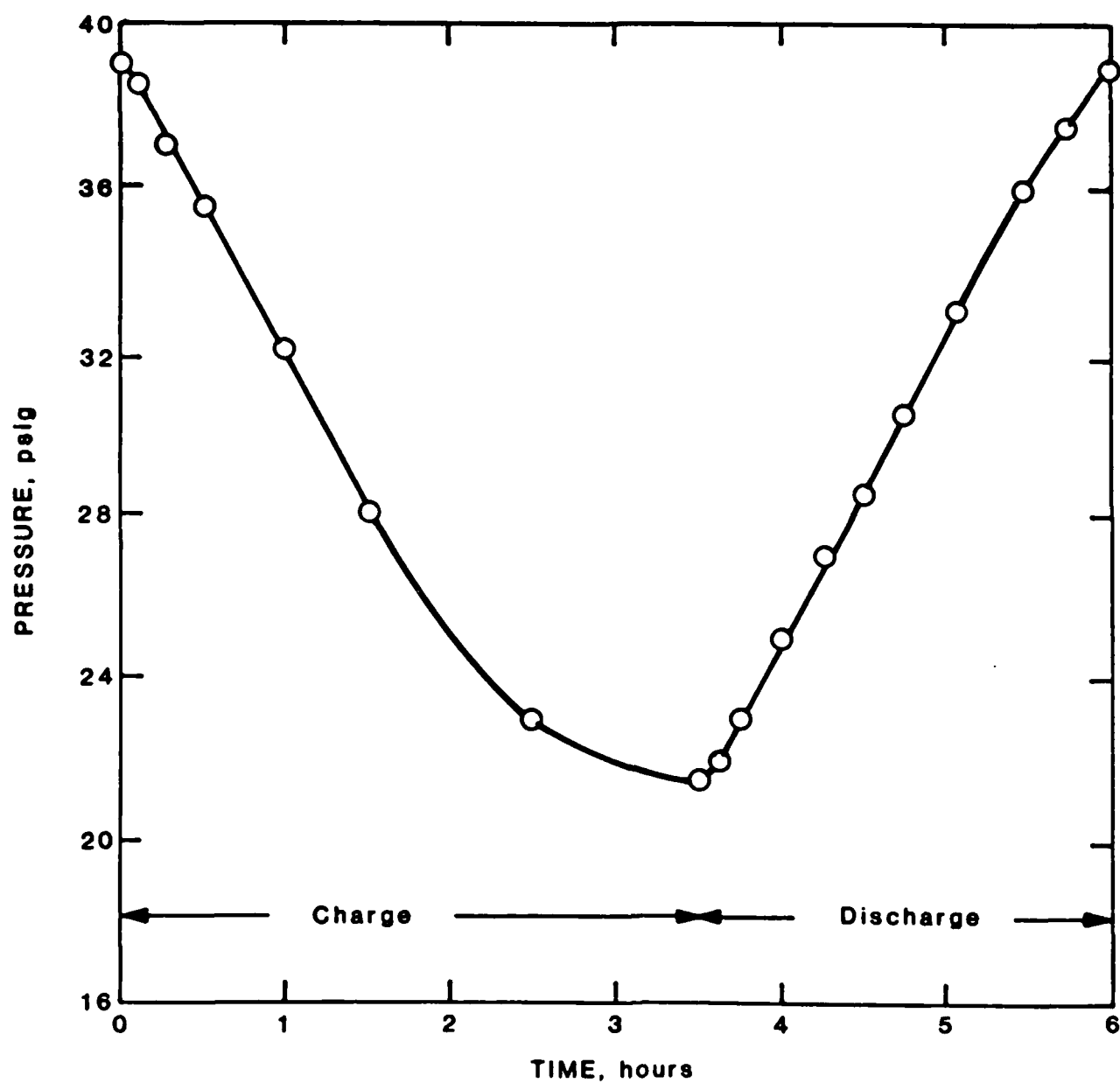


FIGURE 8: PRESSURE PROFILE, CELL #21, CYCLE 47

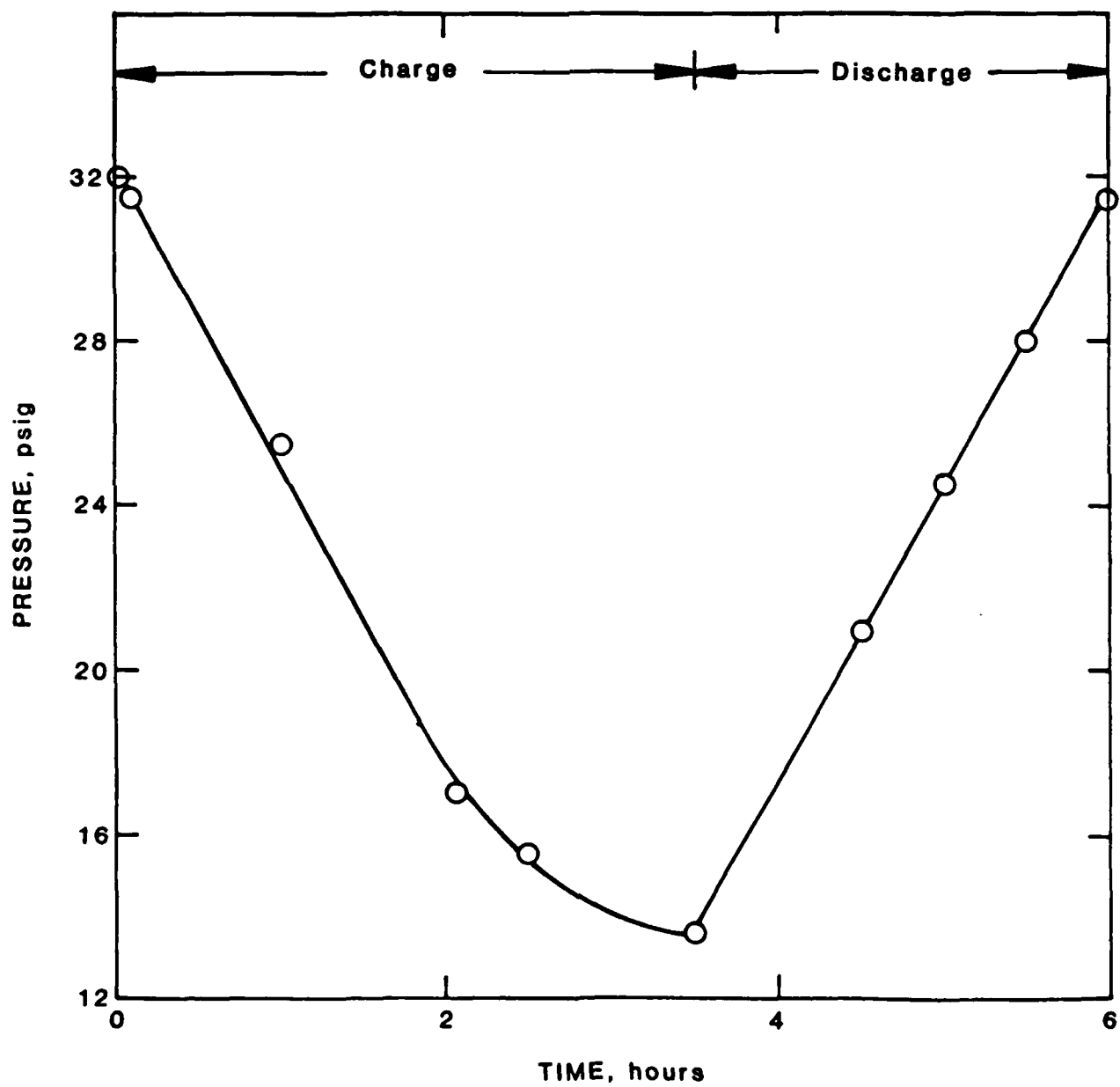


FIGURE 9: PRESSURE PROFILE-CELL #21, CYCLE 334

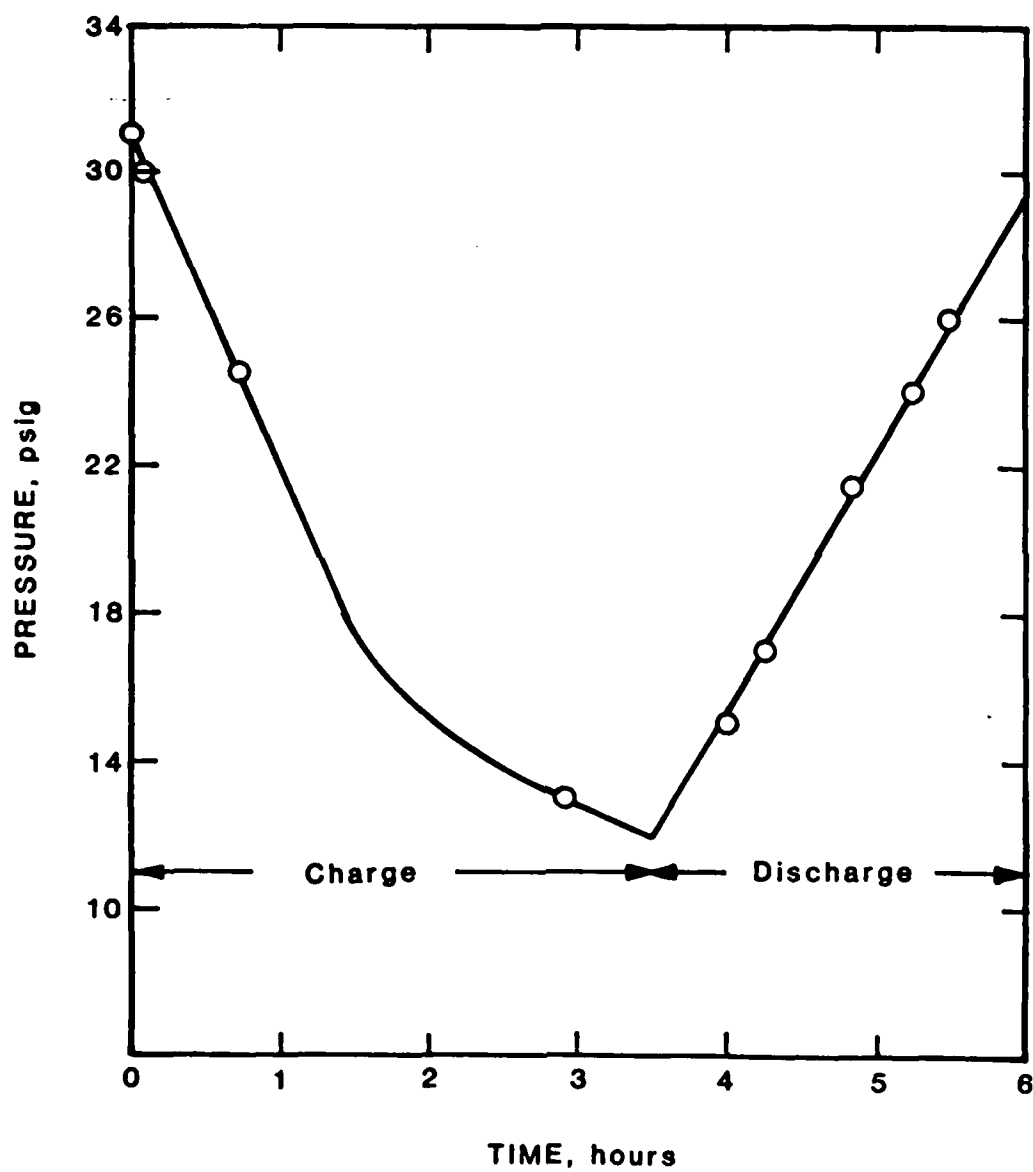


FIGURE 10: PRESSURE PROFILE-CELL #21, CYCLE 562

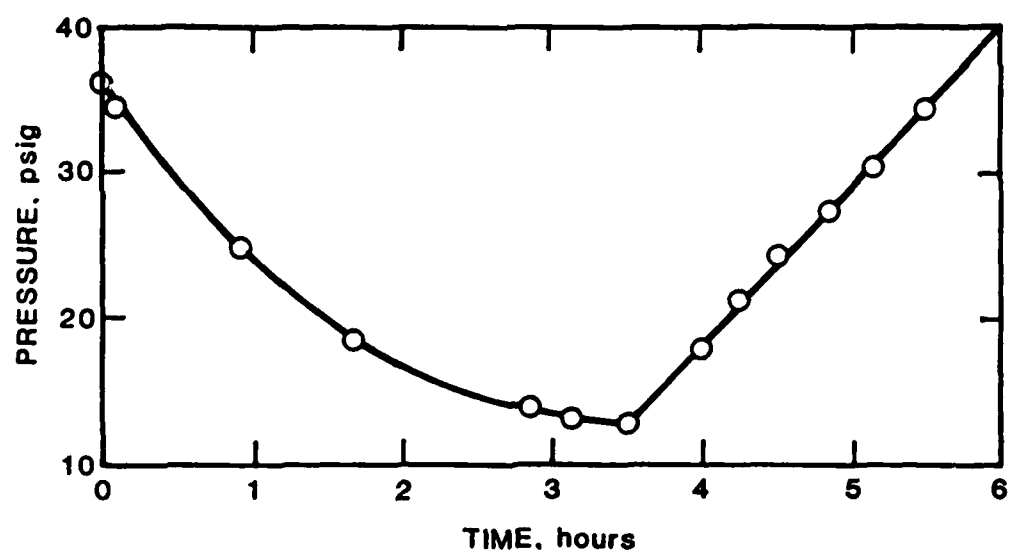
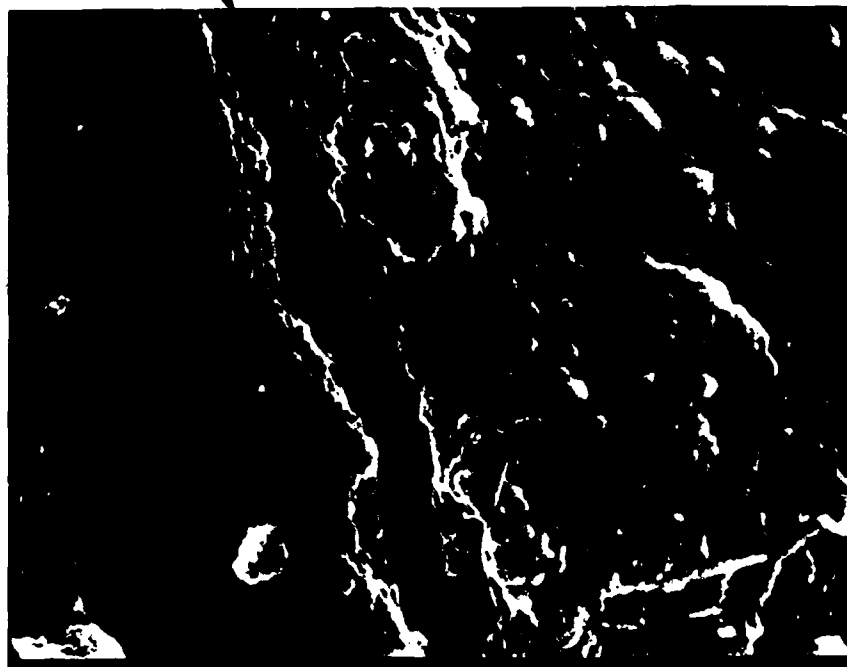
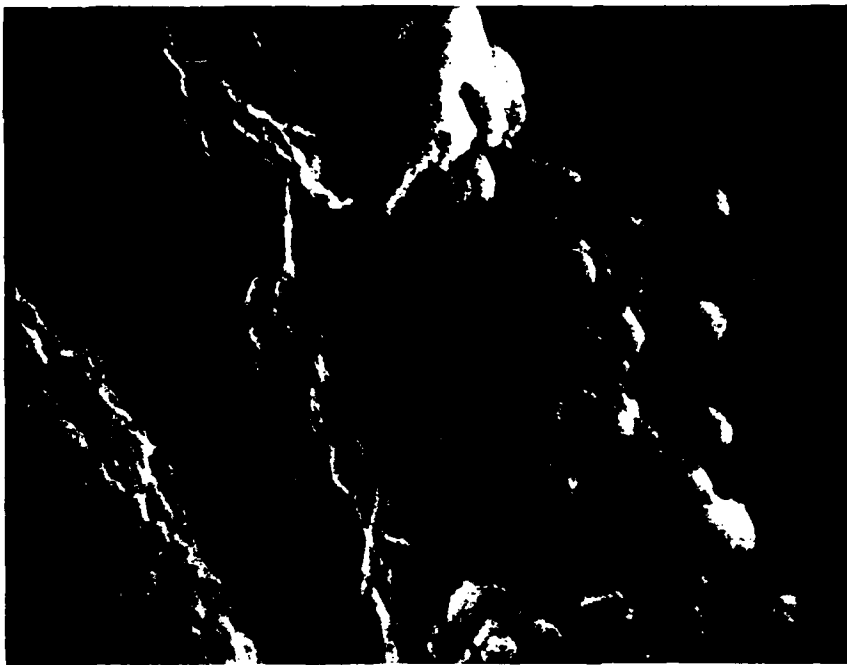


FIGURE 11: PRESSURE PROFILE, CELL #21, CYCLE 1060



Nickel Plack Electrode 6-26-86
Cell #21 1200X

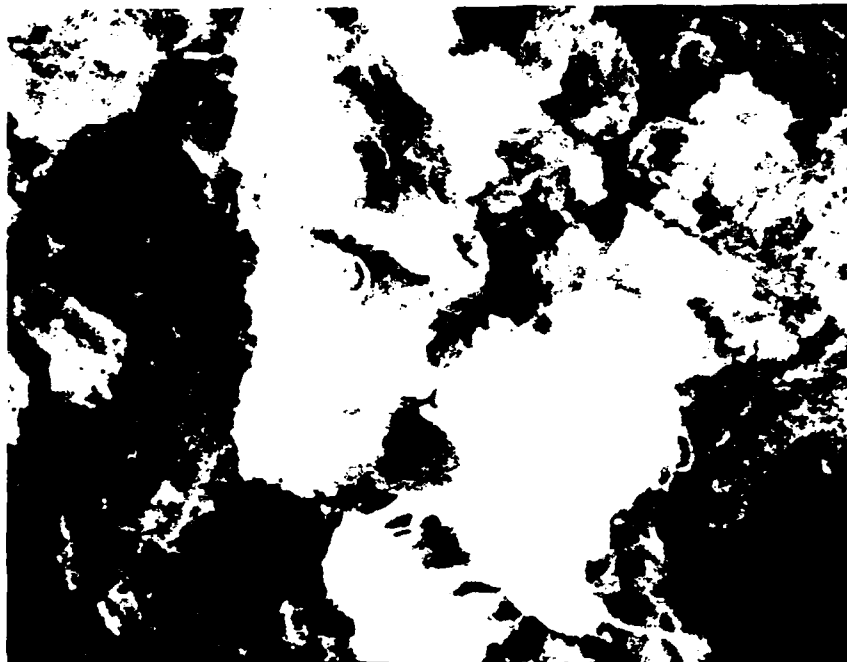


Nickel Plack Electrode 6-26-86
Cell #21 3000X

FIGURE 12 ELECTRON MICROGRAPH, USED Ni ELECTRODE, CELL #21



Nickel Electrode 1200X



Nickel Electrode 3000X

FIGURE 13 ELECTRON MICROGRAPH, FRESH Ni ELECTRODE

begin with, and become denser with use. Conceivable, this has resulted in creating crevices as indicated by the arrow in Figure 12. It is not known whether this crevice exists along the entire surface of the electrode or only at certain spots.

Cell No. 26: This cell contained an ERC roll-bonded nickel electrode and was used for cell characterization tests. The data have already been reported for the interim report for the period July 1984 - June 1985.

After characterization tests were completed, the cell was subjected to cycling. Even though the potential during discharge was high, as with Cell No. 21, the relationship between state of charge and pressure continued to be good. This is shown in Figure 14 for Cycle No. 763. Testing of the cell was stopped after 830 cycles.

Cell No. 30: This cell was fabricated with sintered nickel electrode obtained from the Marathon aircraft battery. Performance evaluation was done at various temperatures and the results are reported in Sec. 3.4. This cell was then subjected to life cycle tests. The cell has completed 800 cycles and tests are continuing. The performance of the cell at cycles 597 and 745 are shown in Figures 15 and 16 respectively.

Cell No. 45: This cell was constructed using a nickel electrode from the GE aircraft battery. The cell was first cycled twice and gave a delivered capacity of 0.325 Ah. Cycling of the cell was started in February 1985 and 418 cycles have been completed. This cell will exhibit the normal operating characteristics.

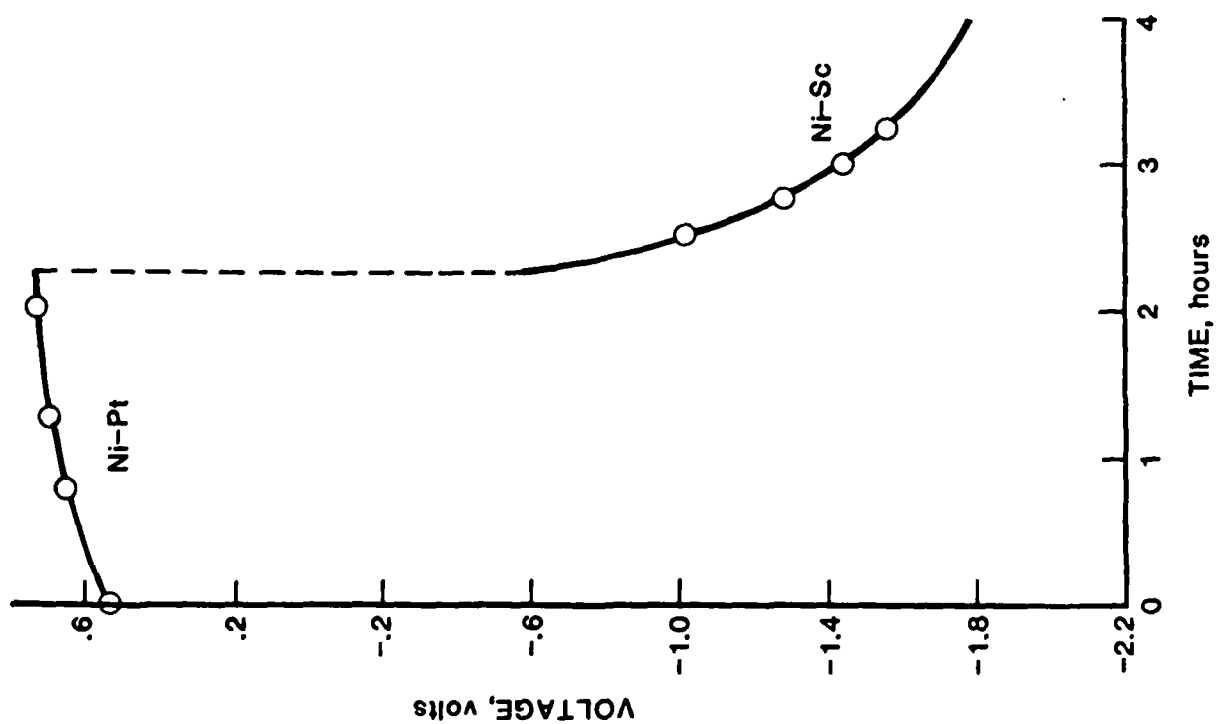
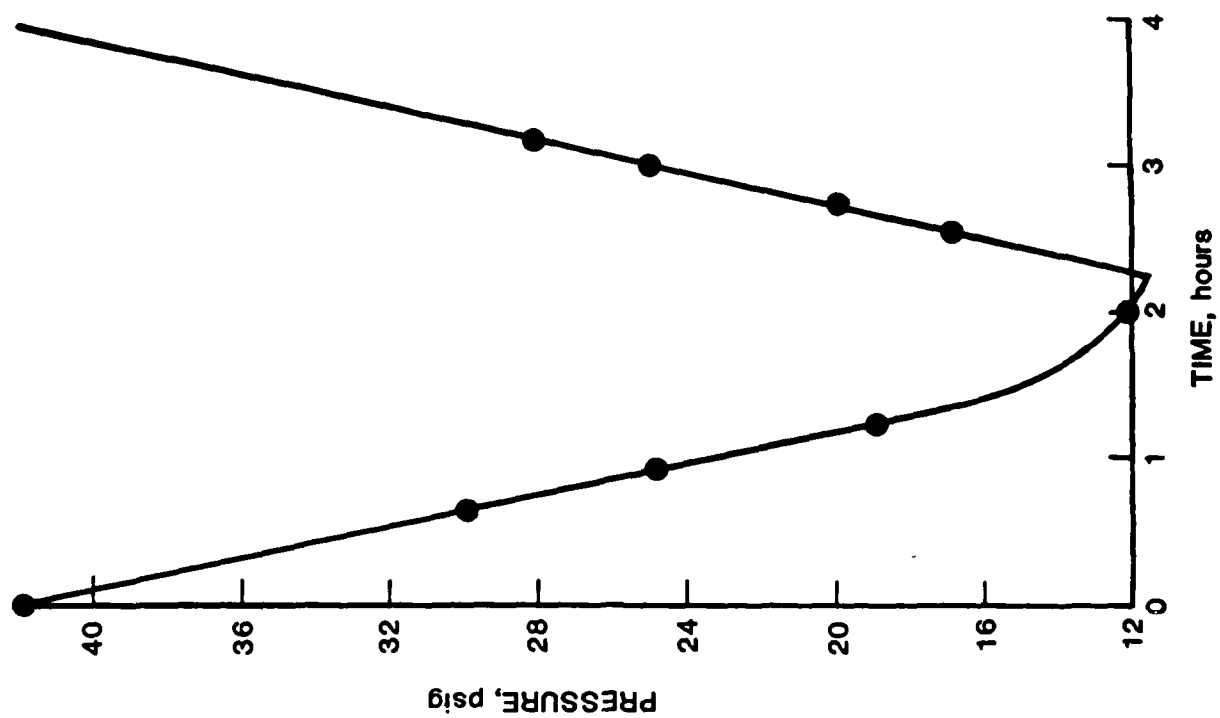


FIGURE 14: PERFORMANCE CHARACTERISTIC CELL #26, CYCLE 763

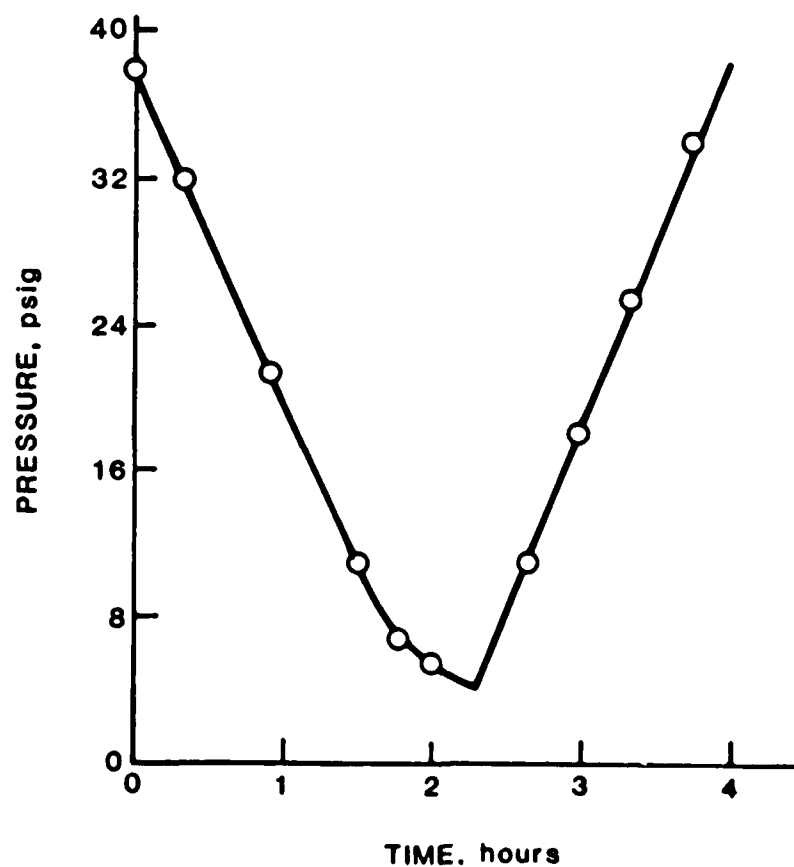
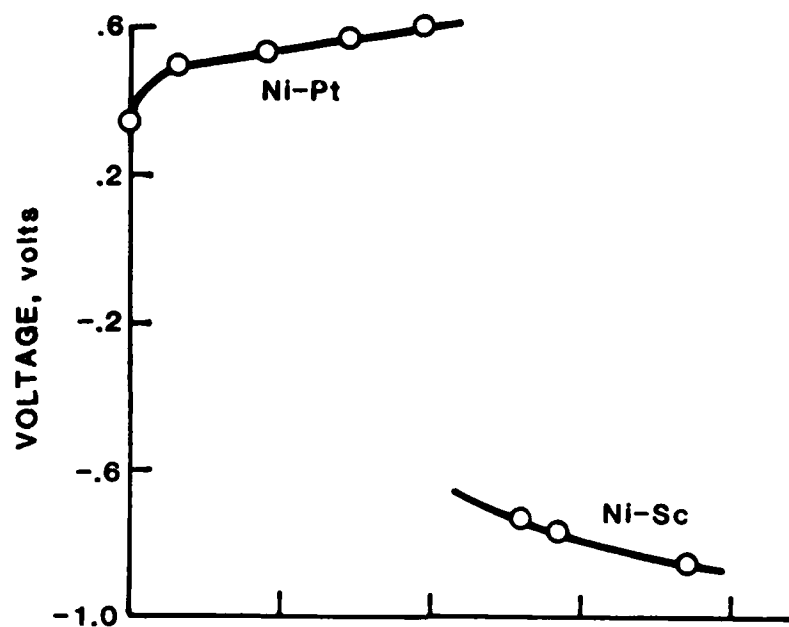


FIGURE 15: PERFORMANCE CHARACTERISTICS
-CELL #30, CYCLE 597

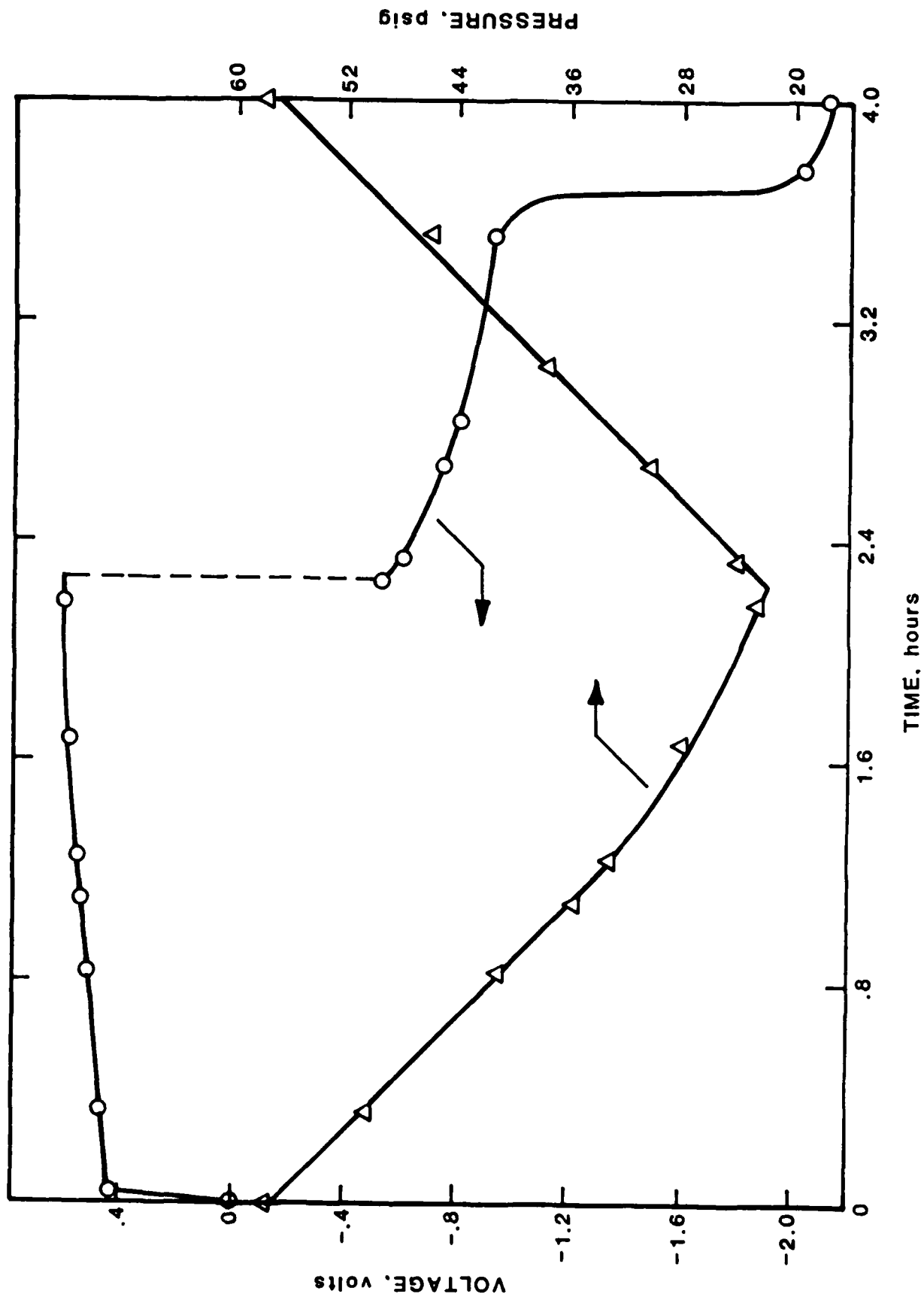


FIGURE 16: PERFORMANCE CHARACTERISTICS CELL #30, CYCLE 795

3.4 Cell Characterization With Respect To Temperature

This phase of the program was originally scheduled to commence during the first year. But characterization at room temperature took longer than planned and therefore the study of temperature effects was started only this month. This delay will not have an impact on the overall program objectives and schedule.

The first series of tests were done on nickel-oxygen pilot Cell 30, fabricated with a sintered (Marathon) electrode. The cell was first charged and discharged at 100 mA at room temperature and a capacity of 0.5 Ah was delivered. In order to accelerate testing, the current was increased to 150 mA and the test was repeated. Keeping the test current the same, the tests were done at different temperatures in the range between 0 and 140°F. The temperature characteristics are shown in Figures 17 to 23 for each of the temperatures.

The results are summarized in Table 1 and the discharge performance at different temperatures are compared in Figure 24. The data indicate that:

- Best delivered capacity is obtained at room temperature.
- Average discharge voltage is inversely proportional to test temperature.
- As evidenced by discharge at 0°F, charge acceptance is better at room temperature than at 0°F.

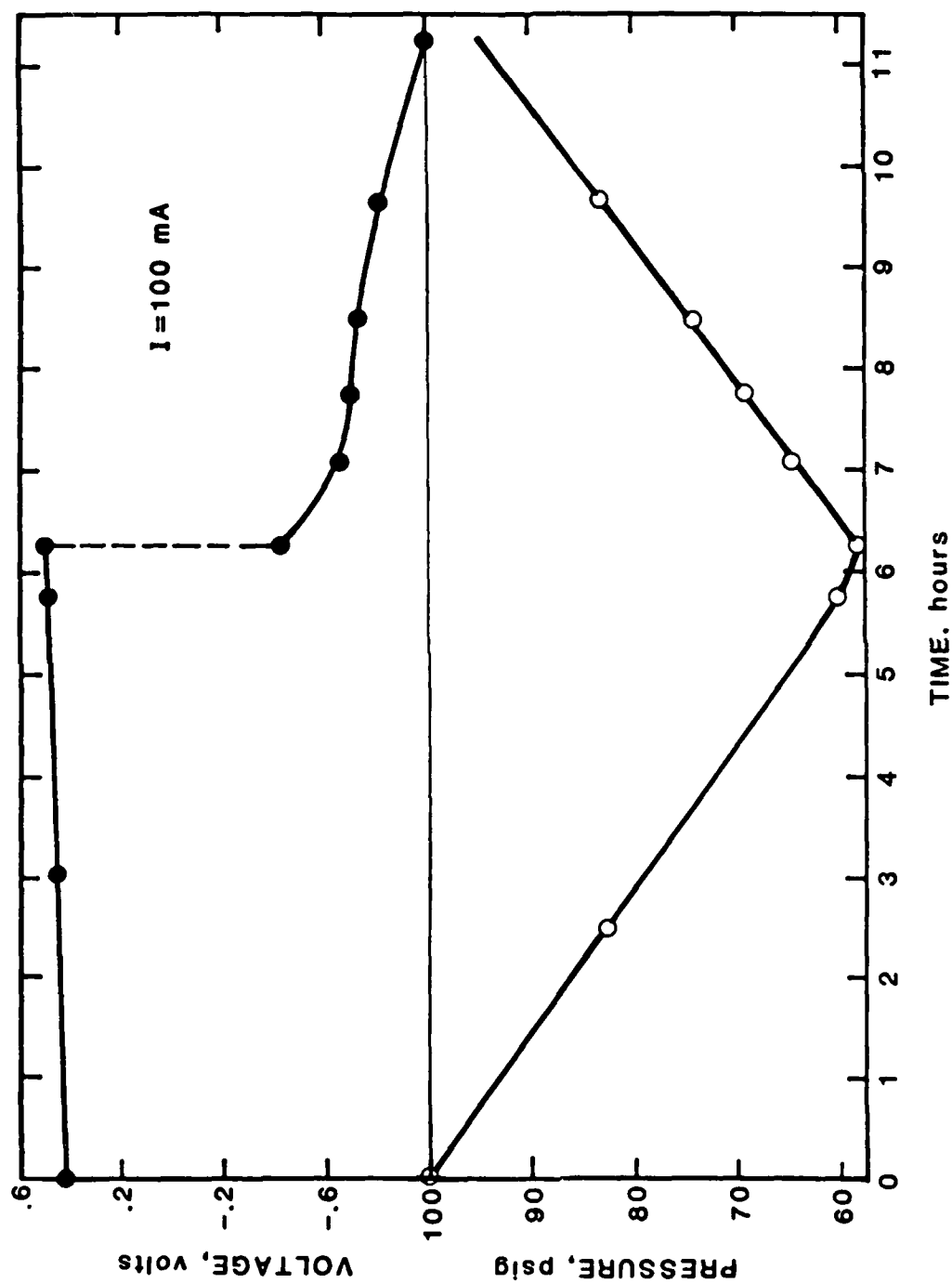


FIGURE 17: PERFORMANCE CHARACTERISTICS-Ni-O₂
CELL #30 AT ROOM TEMPERATURE, 100 mA

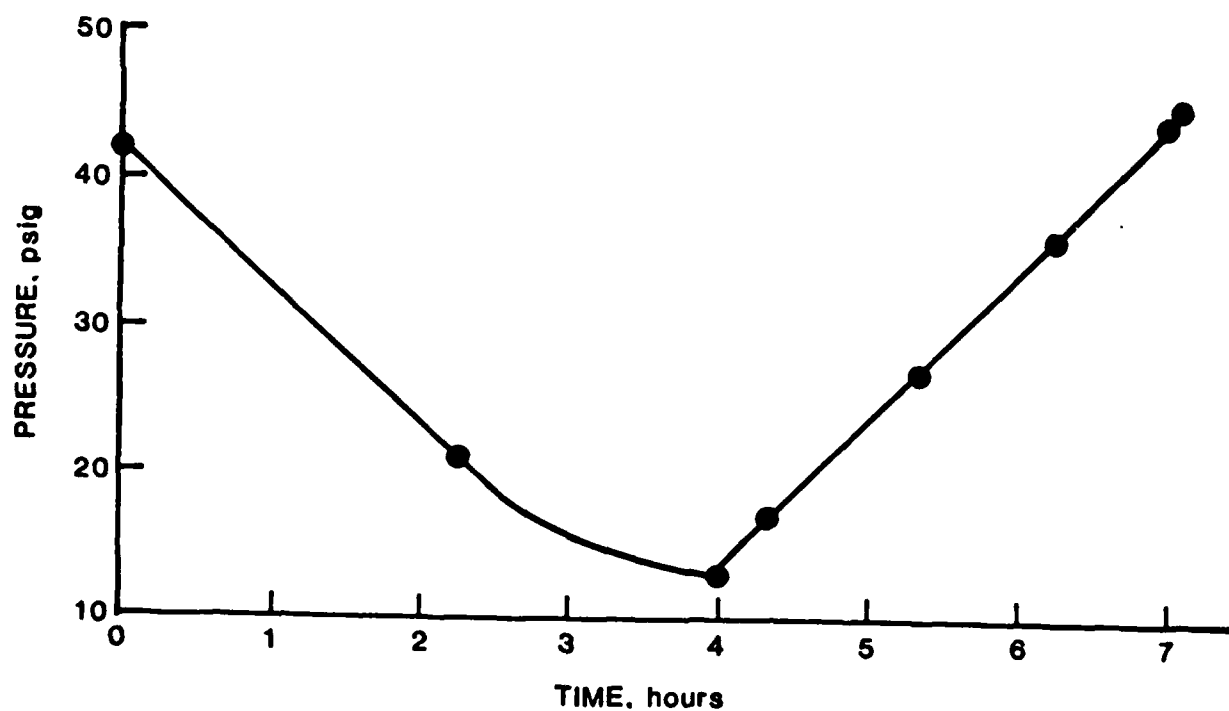
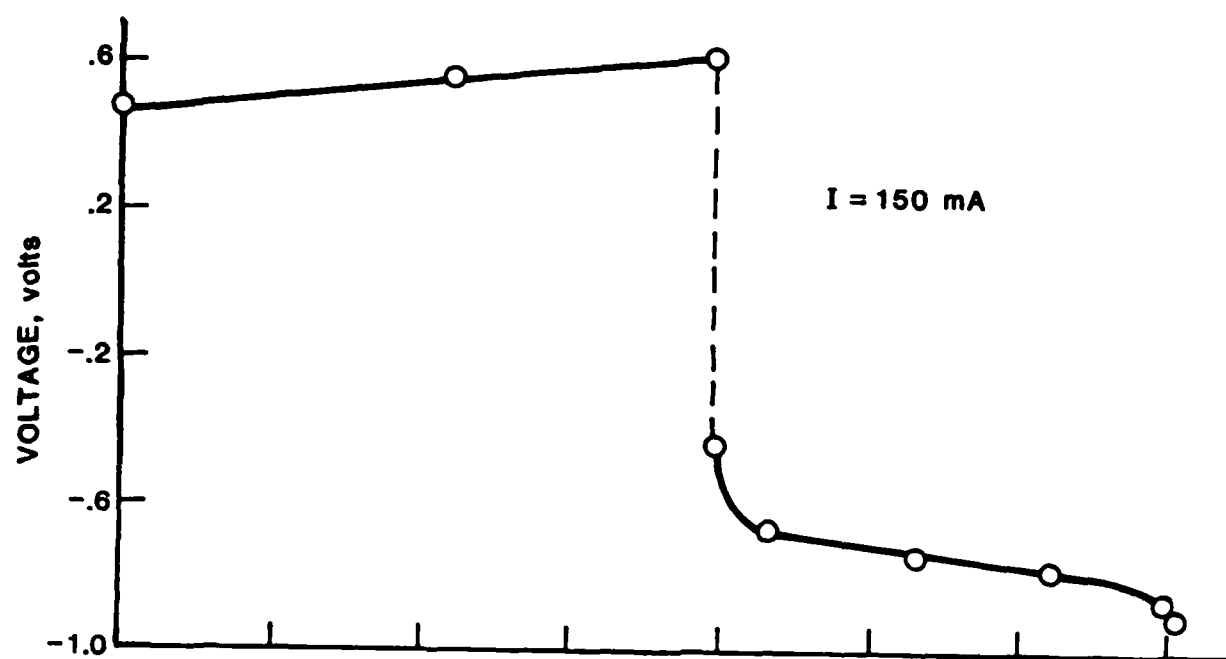


FIGURE 18: PERFORMANCE CHARACTERISTICS-Ni-O₂ CELL #30
AT ROOM TEMPERATURE, 150 mA

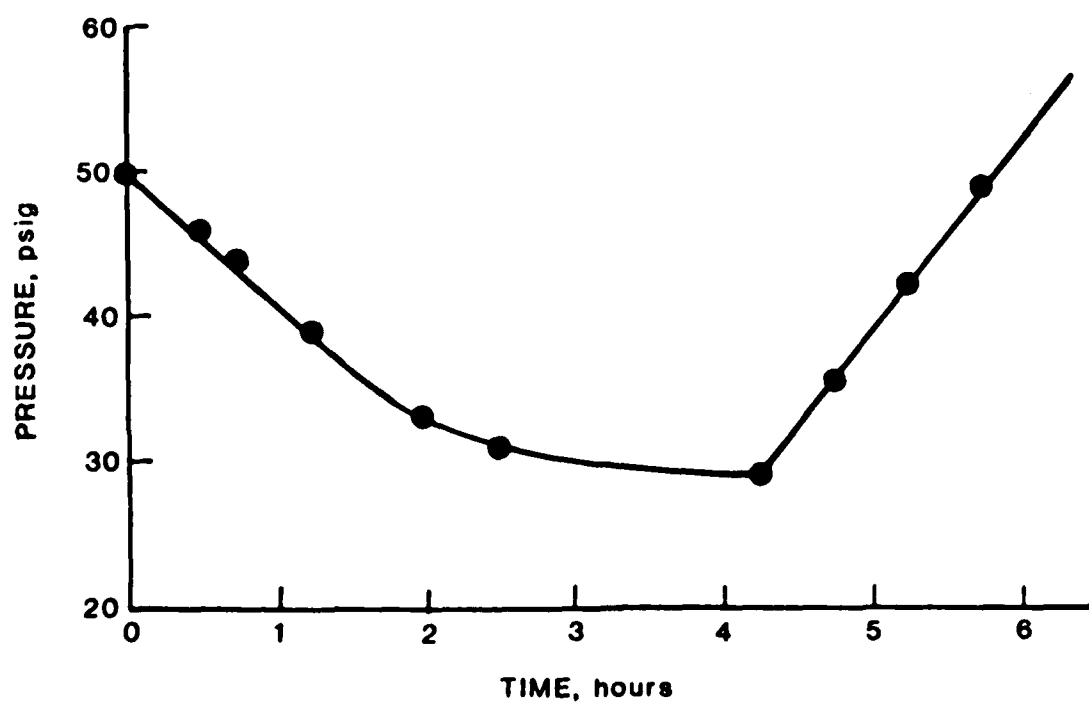
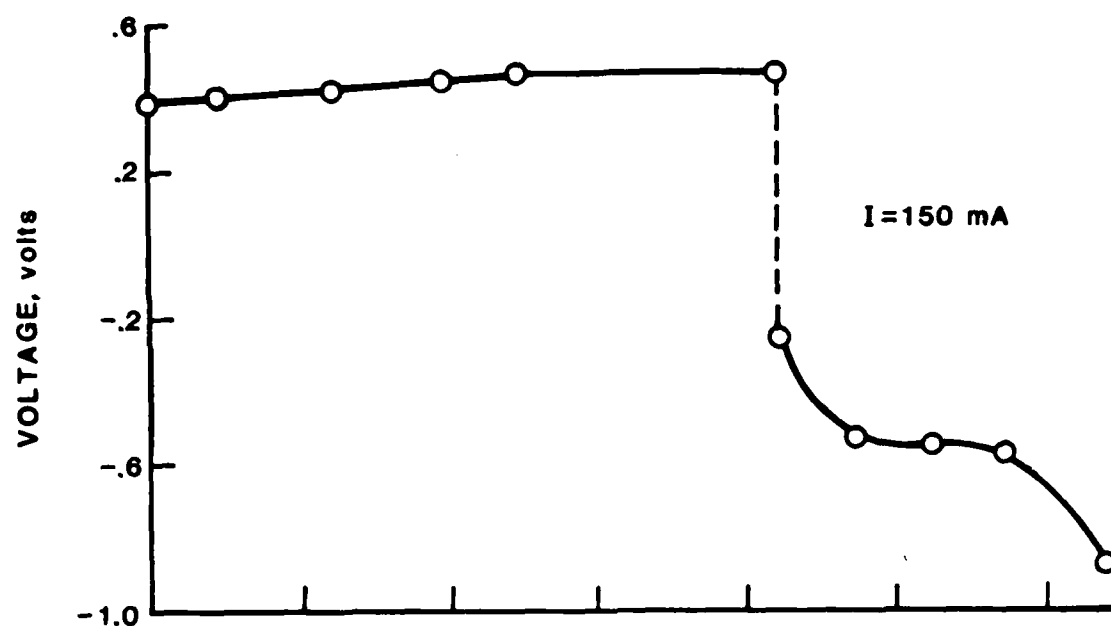


FIGURE 19: PERFORMANCE CHARACTERISTIC-Ni-O₂
CELL #30 AT 140°F

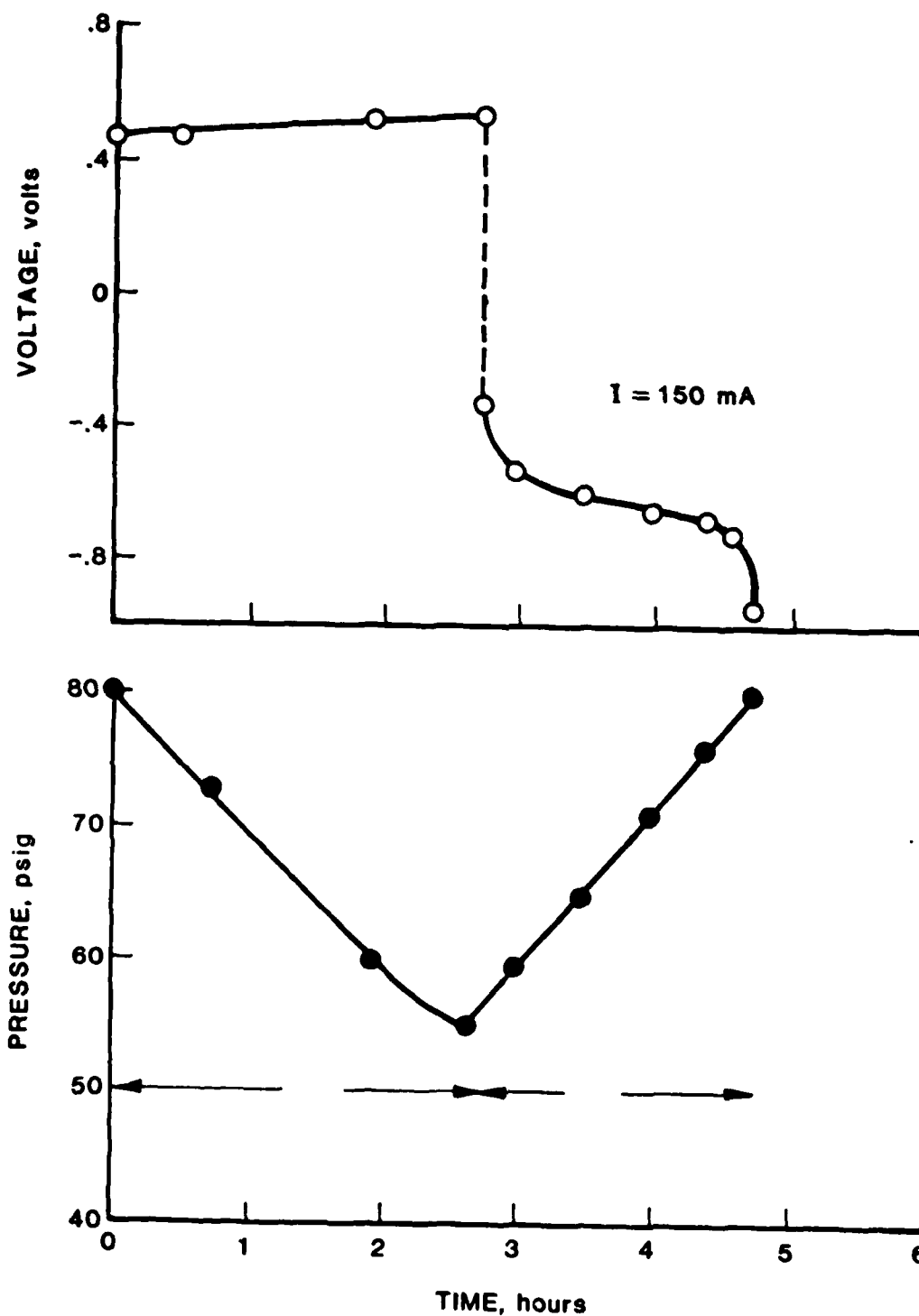


FIGURE 20: PERFORMANCE CHARACTERISTICS-Ni-O₂
CELL #30 AT 100°F

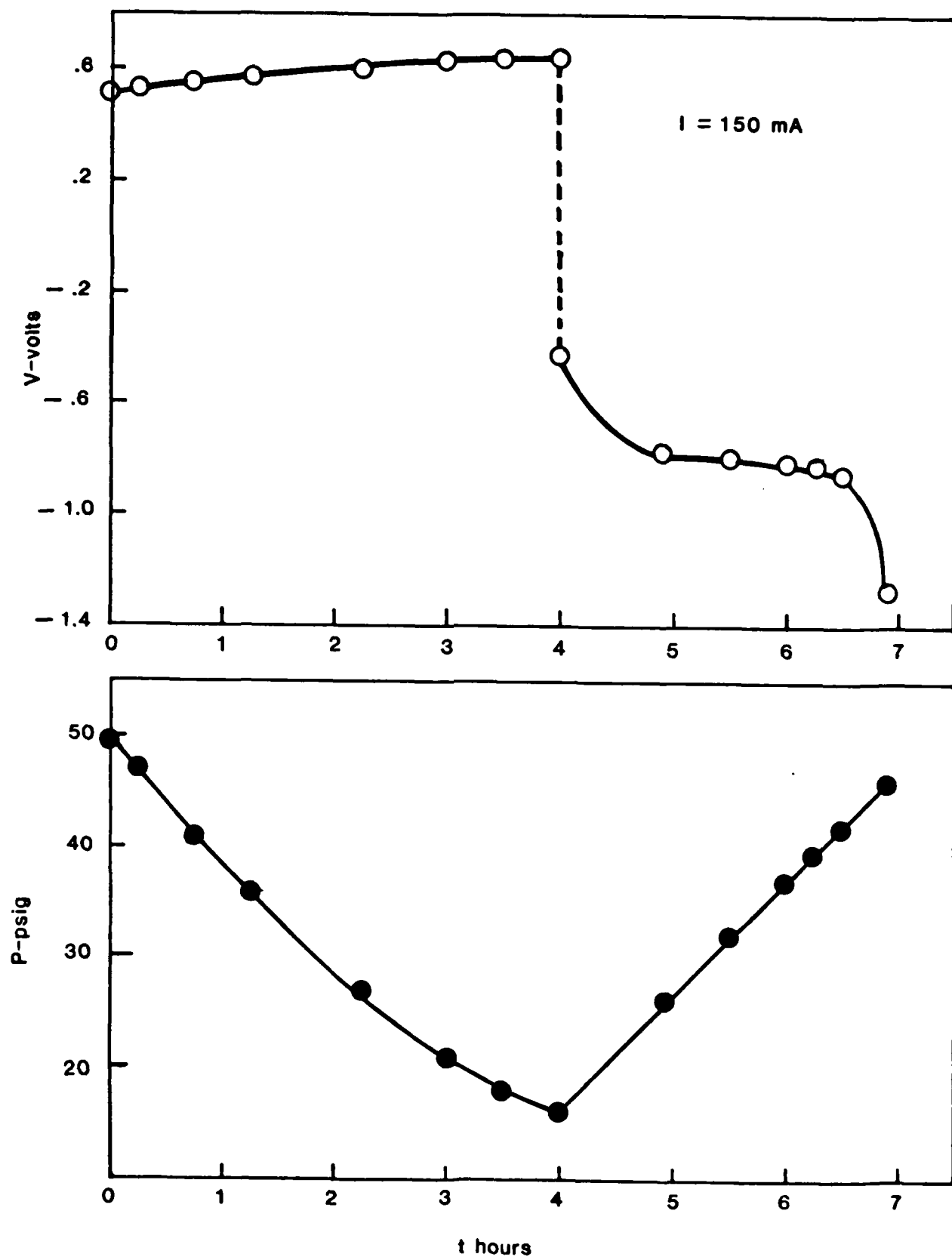


FIGURE 21: PERFORMANCE CHARACTERISTICS-Ni-O₂
CELL #30 AT 0°F

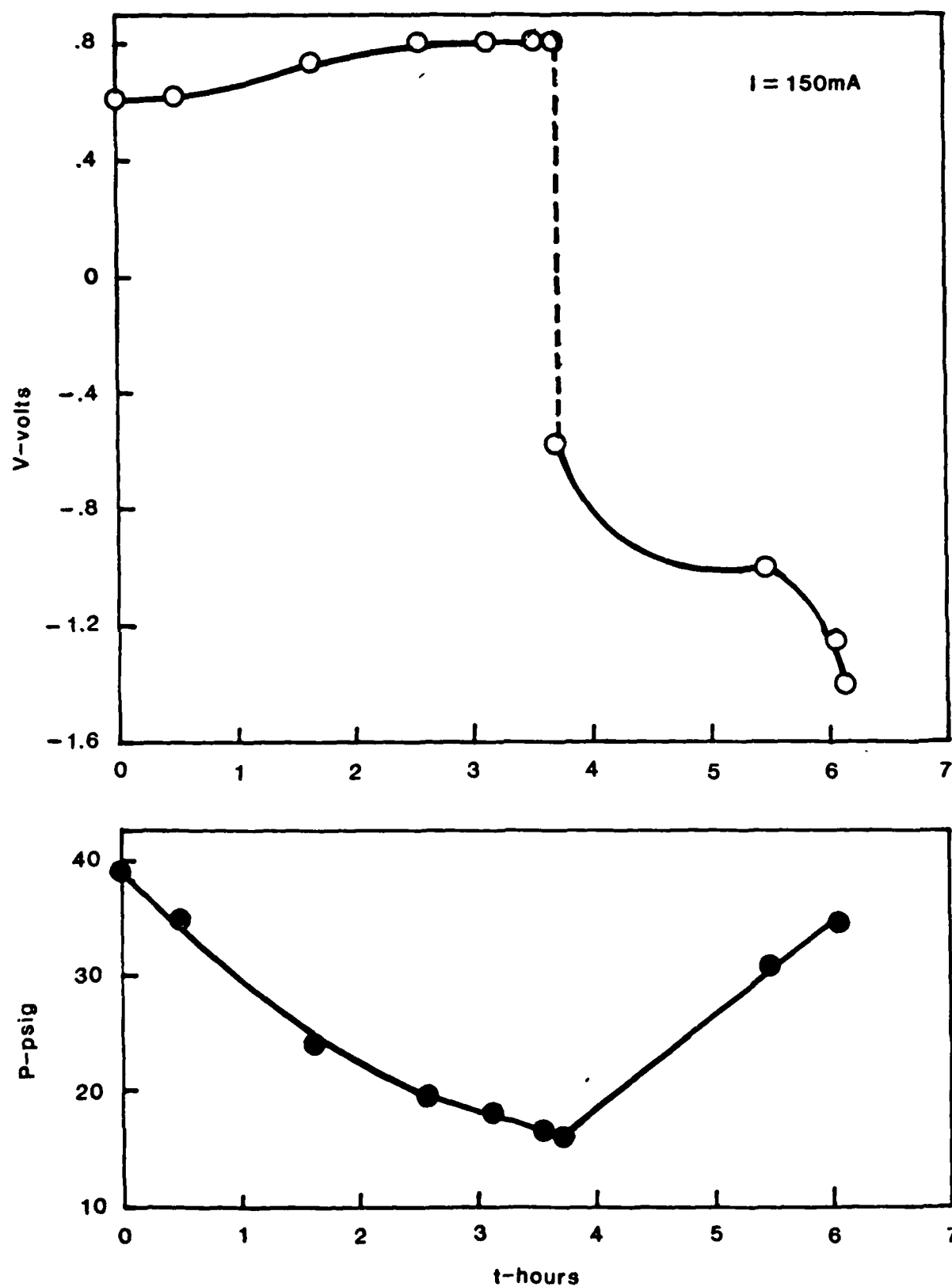


FIGURE 22: PERFORMANCE CHARACTERISTICS-Ni-O₂
CELL #30 AT 60°F

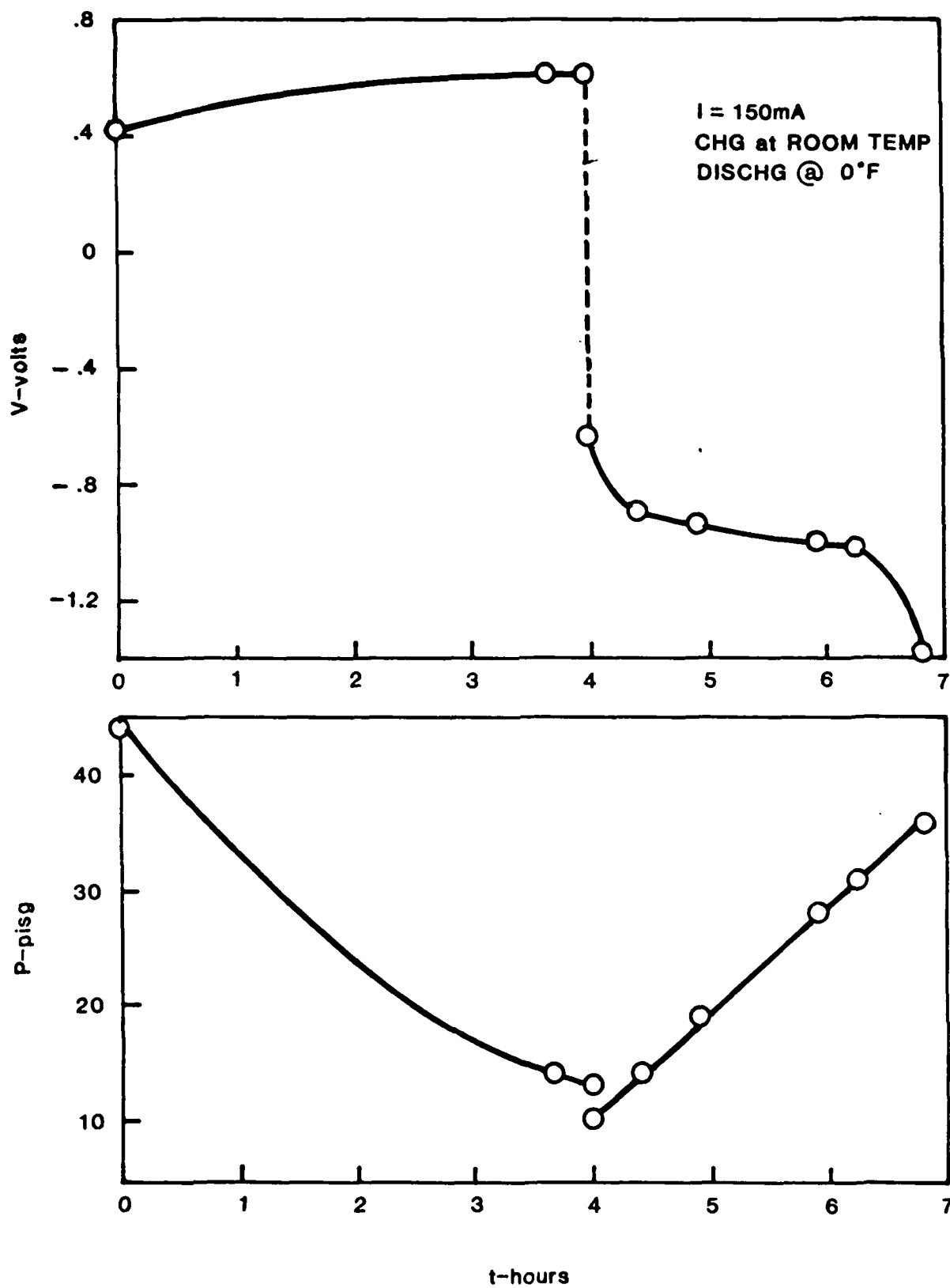


FIGURE 23: PERFORMANCE CHARACTERISTICS-Ni-O₂
CELL #30 AT 0°F

TABLE 1

CELL PERFORMANCE AT DIFFERENT TEMPERATURES

Ni-O₂ Cell 30

Ni Electrode: Sintered, Marathon

<u>Cycle No.</u>	<u>Charge</u>			<u>Discharge</u>		
	<u>T°F</u>	<u>Ah</u>	<u>ΔP</u>	<u>T°F</u>	<u>Ah</u>	<u>ΔP</u>
1	Room	.625	42	Room	.500	45
2	100	.413	25	100	.300	24
3	140	.638	21	140	.326	26
4	60	.600	34	60	.432	30
5	0	.558	23	0	.362	21
6	Room	.600	31	0	.425	26
7	Room	.600	29	Room	.458	32

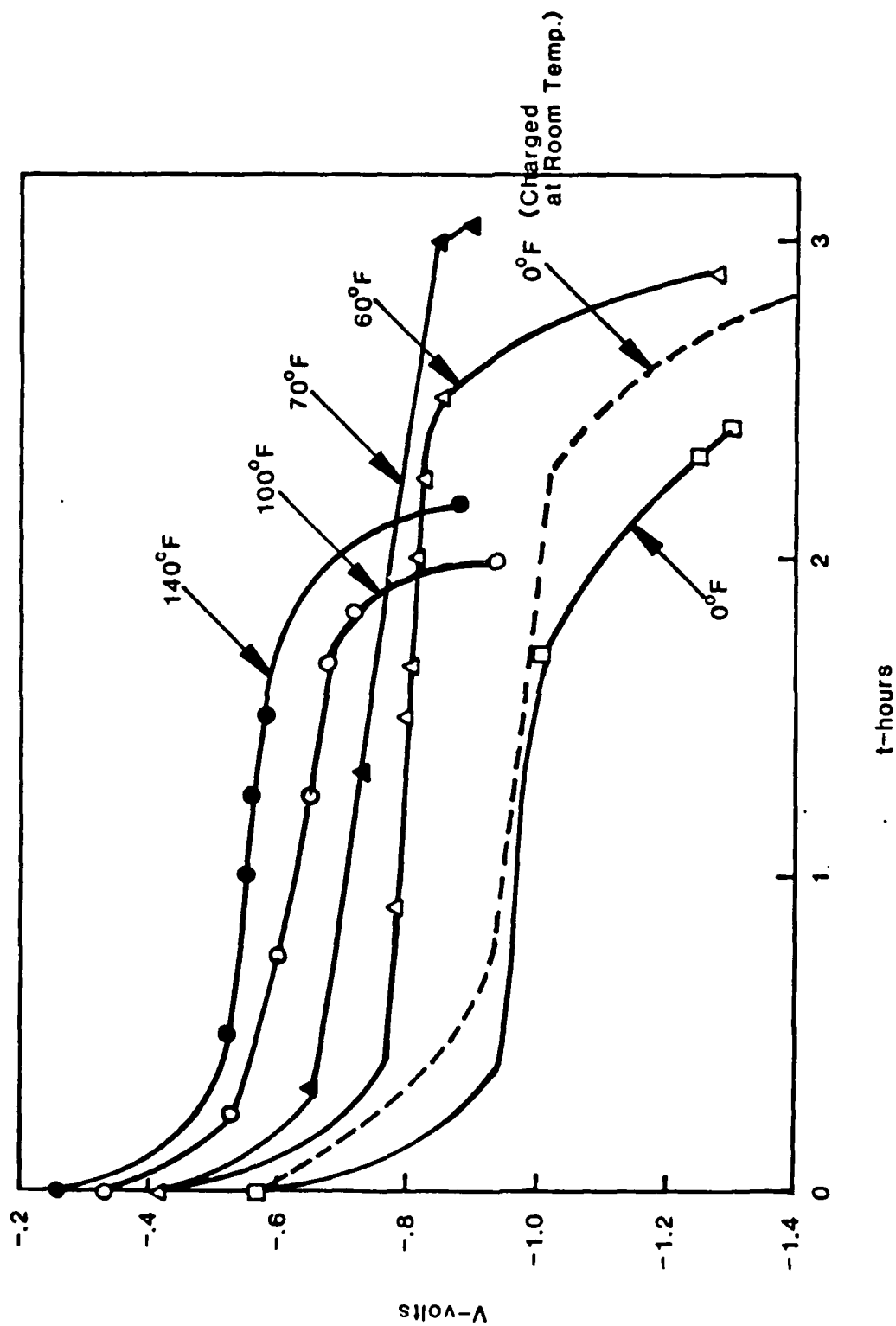


FIGURE 24: DISCHARGE PERFORMANCE OF Ni-O₂ CELL #30
AT DIFFERENT TEMPERATURES

The effect of variations in ambient temperature on cell pressure during open circuit stand was also measured. Life tests of Cells #21 (sintered Ni), 25 and 26 (roll-bonded Ni) were stopped after they had undergone 1,026, 766 and 795 cycles, respectively. In order to compare the variation in pressure under identical environmental and state of charge conditions, all three cells were fully charged. The pressure at the end of charge was set at 10 psig for each cell.

The cells were next allowed to stand on open circuit and the room temperature and cell pressure were monitored daily.

The initial preset value of 10 psig increased slightly in the first two days, after which it remained constant. In the temperature range of 19-26°C, all three cells exhibited very little change in pressure. The results, plotted in Figure 25, show that over the temperature range investigated, the values of pressure of all three cells remain steady with very little fluctuations on open circuit stand. However, it should be pointed out that during charge and discharge at higher rates, temperature excursions could become significant.

3.5 Single Electrode Potentials

In order to monitor the potentials of individual electrodes and identify the electrode responsible for cell failure, a test fixture was designed and built. In addition to the three electrodes, the assembly was designed to accommodate a cadmium wire to be used as

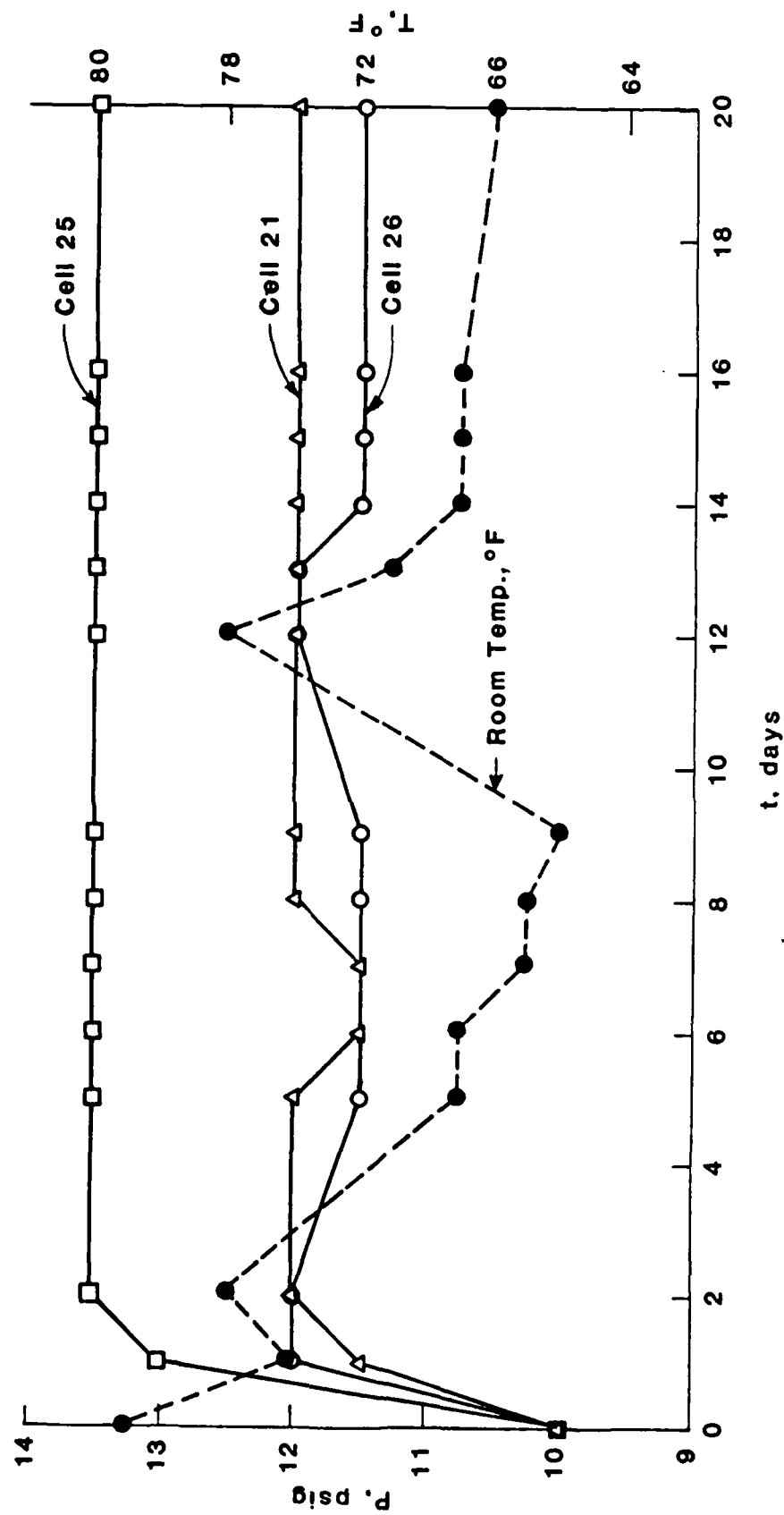


FIGURE 25: VARIATION OF CELL PRESSURE WITH AMBIENT TEMPERATURE ON OPEN CIRCUIT STAND

a reference to monitor the potential of each working electrode.

Cell No. 25 was built in the test fixture employing ERC roll-bonded nickel electrode. Test data to 650 cycles were given in the last interim report. Life cycle tests were continued and a change in performance was first noticed during cycle 730. The performance started to deteriorate with high values of polarization and lowered values of capacity. As can be seen from the single electrode potentials in Figure 26, the gas electrode is still performing well and the mechanism of failure is attributed to the high polarization of the nickel electrode. For purposes of comparison, similar values for Cycle No. 624 are given in Figure 27.

Despite the increased polarization of the nickel electrode, the Ni-O₂ cell continues to exhibit linearity of pressure with time and tapering of pressure at the conclusion of charge; this characteristic is shown in Figure 28.

Test results of Cell No. 25 further confirm the excellent suitability of the nickel-oxygen cell to function as an indicator of the state of charge of the main battery. The analysis of the data from this series of tests shows that:

- 1) Since the main battery and pilot cell are run in tandem and since the failure of the pilot cell is caused by the decay of the nickel electrode, the positive plate of the main battery would also fail at the same time. This would result in the usefulness of the main battery being terminated, and as such no further monitoring

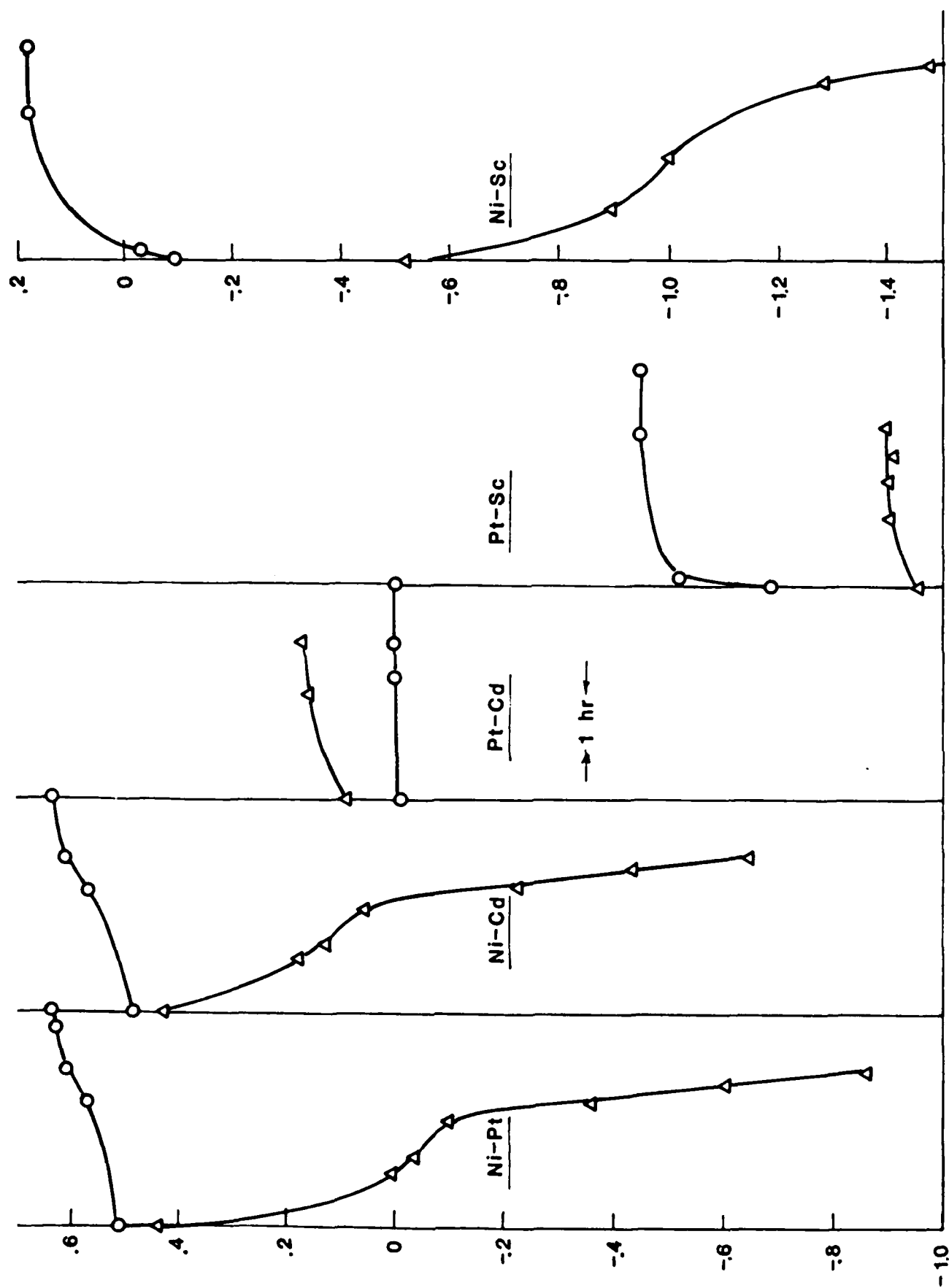


FIGURE 26: SINGLE ELECTRODE POTENTIALS-CELL #25, CYCLE 730

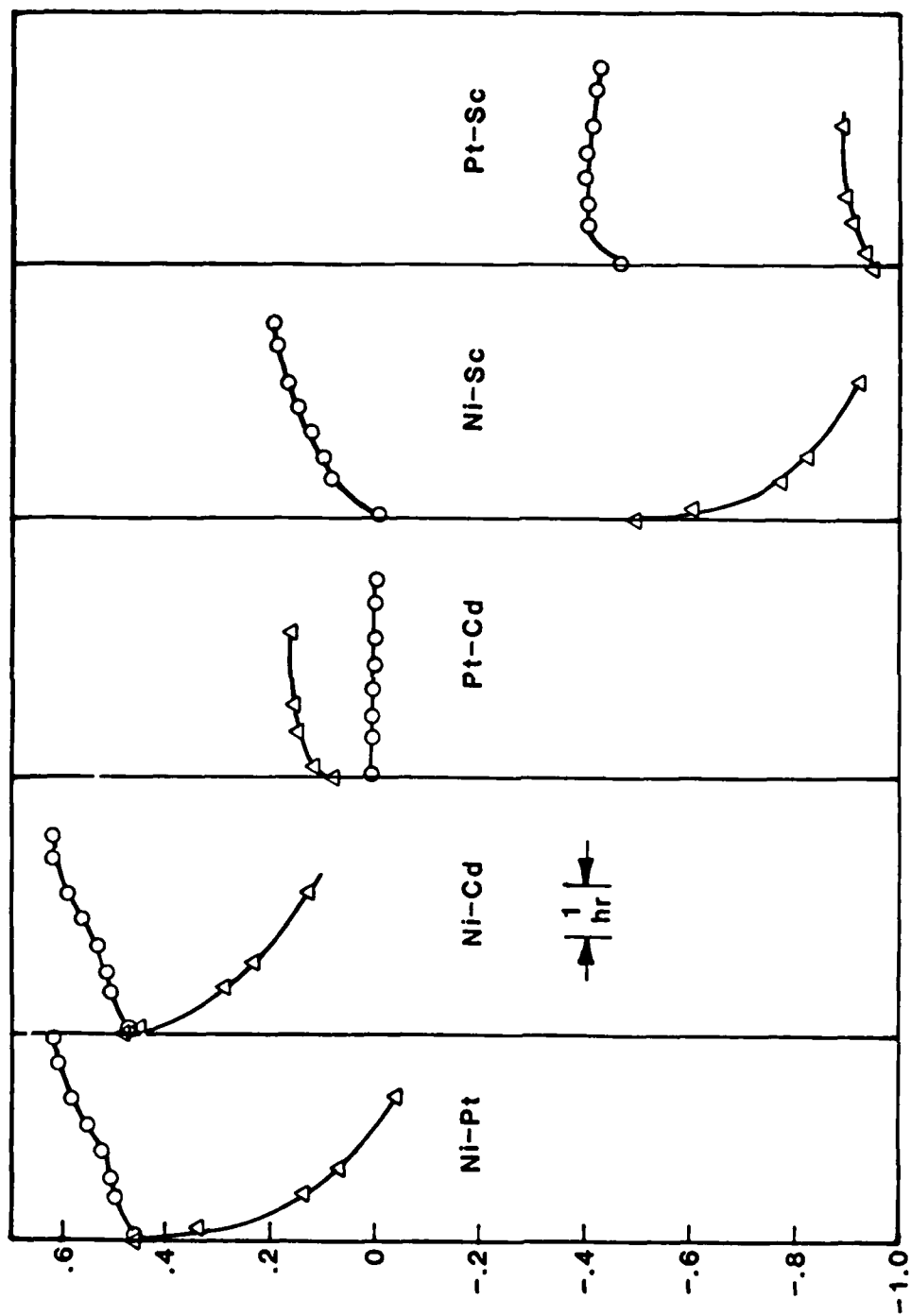


FIGURE 27: SINGLE ELECTRODE POTENTIALS-CELL #25, CYCLE 624

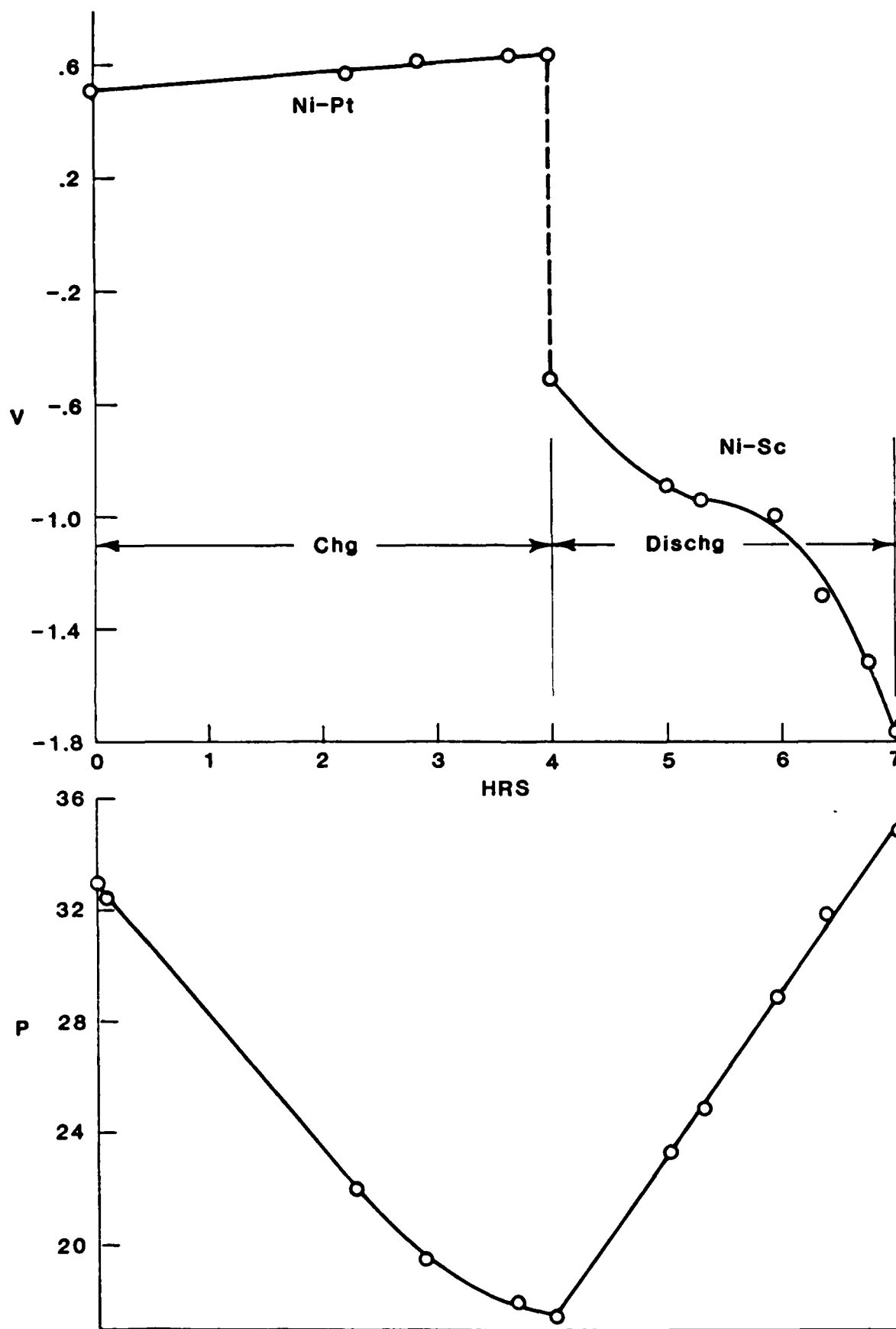


FIGURE 28: PRESSURE PROFILE-CELL #25, CYCLE 730

would be required.

- 2) Even if the main battery does not fail at the same time, the pilot cell would still have the capability to track the pressure, despite the deterioration of the nickel electrode.

Life cycle tests were discontinued and Cell #25 was used to evaluate variations in cell pressure with temperature on open circuit stand (Sec. 3.4).

Another experimental cell (#41) was constructed in a test fixture with the cadmium reference electrode. The design of this cell was similar to that of Cell #25, the only difference being the type of nickel electrode. Cell #25 was fabricated with ERC roll-bonded nickel and data on cycle life and single electrode potentials were obtained. Cell #41 was built with a sintered nickel electrode from a fresh aircraft cell manufactured by Marathon Battery Company. This cell was tested under the same conditions employed for Cell #25 and since all other parameters remain the same, the test data will provide a means for directly comparing the performance characteristics of the two types of nickel electrodes. Cell #41 exhibited the following parameters when newly built:

Delivered Capacity = 0.46 Ah @ 100 mA

End of Discharge Volts

Ni-Pt	0.020
Ni-Cd	0.299
Ni-Sc	0.841
Pt-Cd	0.319
Pt-Sc	0.822

Cycling of the cell was started at 100 mA with charge and discharge times being 4 and 3 hours respectively--the same parameters used for Cell #25. Single electrode potentials of Cells #41 and 25 for comparable cycles are shown in Figs. 29 and 30. The cell has completed 784 cycles and tests are continuing. The data for Cycle #736 are shown in Fig. 31.

3.6 Aircraft Battery Tracking System

Investigations to determine the tracking characteristics of the Ni-0₂ cell when operated in tandem with commercial aircraft batteries have continued. The test equipment, designed and built in-house, consists essentially of a constant current power supply, a cycling unit with adjustable times and current and a digital display which converts the pressure of the Ni-0₂ cell into percent state of charge. The unit also has provisions to terminate the current when a full charge of 100% is reached.

A 13-cell stack of SAFT aircraft cells was run in tandem with an Ni-0₂ cell made with an identical nickel electrode in the first series of tests. After initial evaluation and calibration, the system was operated in the automatic cycling mode, operating specifications of which are given in Table 2. After ensuring that the system functioned properly, tests were started to investigate the relationship between state of charge and delivered capacity.

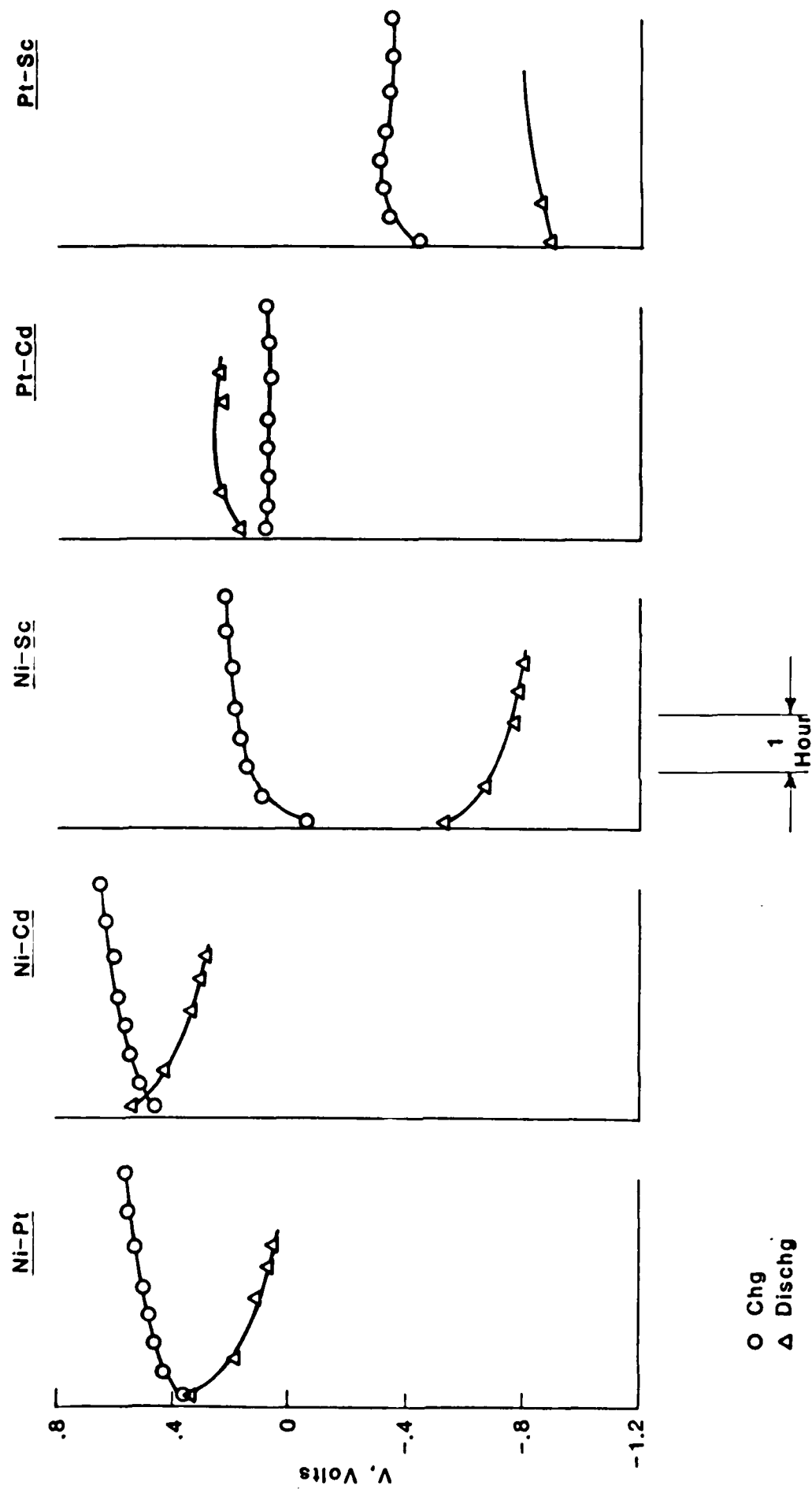


FIGURE 29: SINGLE ELECTRODE POTENTIALS-CELL #41, CYCLE 65

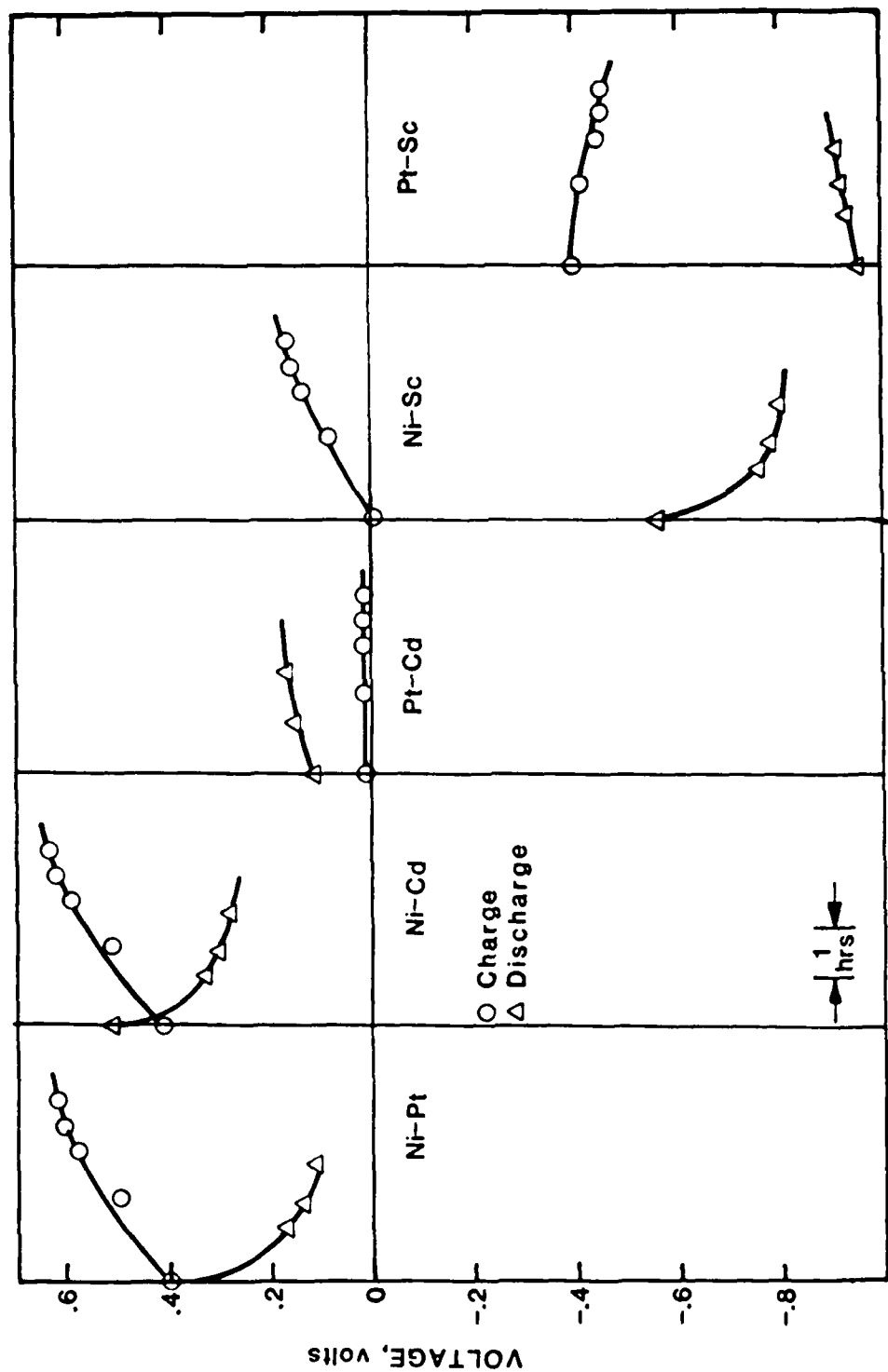


FIGURE 30: SINGLE ELECTRODE POTENTIALS-CELL #25, CYCLE 73

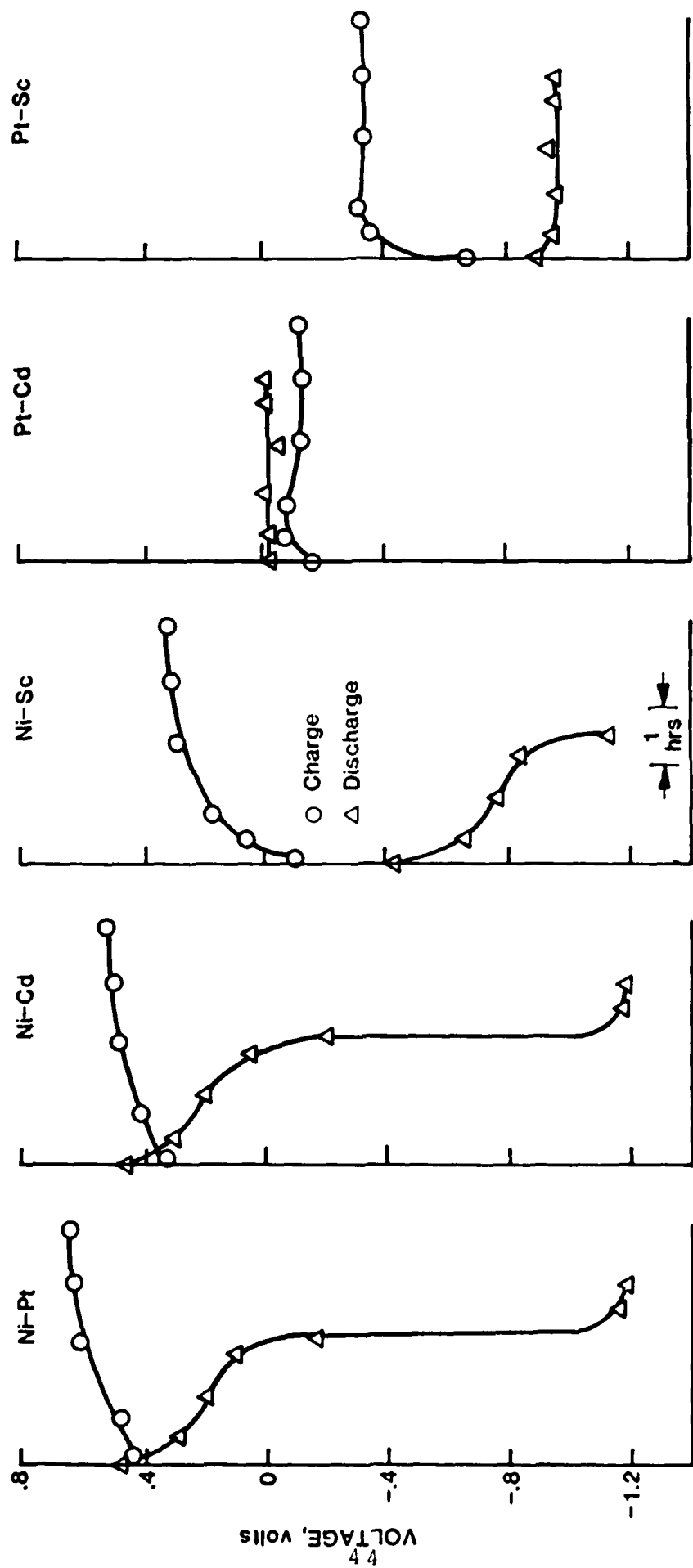


FIGURE 31: SINGLE ELECTRODE POTENTIALS-CELL #41, CYCLE 736

TABLE 2
TRACKING CYCLER SPECIFICATIONS

	<u>SAFT</u>	<u>Ni-O₂</u>
From graph, total time to end of discharge	7.45 hrs	7.55 hours
Charge time	2.65	2.75
Discharge time	4.80	4.80
Discharge current	3.6A	46 mA
Actual delivered capacity	17.28 Ah	.221 Ah
<hr/>		
Discharge		
DOD	75%	75%
Capacity to be removed	12.95 Ah	.166 Ah
I	3.6 A	46 mA
t	3.6 hours	3.6 hours
<hr/>		
Charge		
Overcharge	11%	11%
Capacity to be put in	14.39 Ah	.184 Ah
I	3.6 A	46 mA
t	4.0 hours	4.0 hours
<hr/>		
i.e. cyclor to be calibrated to,		
Charge	4.0 hours @ 3.6 A	4.0 hours @ 46 mA
Discharge	3.6 hours @ 3.6A	3.6 hours @ 46 mA

1. Set cycler to "manual" operation.
2. Charge until fuel gauge reaches the desired state-of charge.
3. Discharge to end battery voltage of 11.0 V.
4. Repeat steps 2 and 3 for a different state of charge.

The series of tests were performed in both directions with the state of charge values going down in steps from 100% and going up in steps from 15%. The test data are summarized in Table 3 and a plot of delivered capacity vs. state of charge is shown in Figure 32.

During each discharge, (starting from a particular state of charge), the fuel gauge reading was monitored continually. As shown in Figures 33 and 34, the state of charge was linear with the capacity removed and the slope of the line was found to be independent of the state of charge. A typical profile of percent charge and battery voltage is shown in Figure 35.

The results obtained from this series of tests indicate:

1. Excellent capability of the pilot cell to track the state of charge of the main battery.
2. Linearity of state of charge and capacity (Figure 32).
3. Constant slope of state of charge vs. capacity curves, (Figures 33 and 34).
4. Reproducible data.

The test results also identify one parameter which required further study. Since the battery is discharged fully to the same potential each time, under ideal conditions,

TABLE 3
STATE OF CHARGE VS. DELIVERED CAPACITY

CYCLE NO.	CHARGE		DISCHARGE		Ah out/Ah in %
	% CHG.	Ah	% CHG.	Ah	
29	100	15.84	0	15.30	97
30	90	14.40	0	13.75	95
31	80	12.78	0	12.38	97
32	60	8.78	4	8.60	98
33	40	5.29	8	4.79	91
34	30	3.54	7	3.48	98
35	22	2.41	7	2.28	95
36	10	.54	6	.54	100
37	15	.58	11	.54	93
38	20	1.62	9	1.50	93
39	30	3.42	8	3.42	100
40	40	5.40	2	5.69	105
41	50	7.06	4	6.88	97
42	60	9.47	0	9.04	95
43	70	10.80	2	10.51	97
44	80	12.42	3	11.95	96
45	90	14.40	1	13.68	95
46	100	18.58	-5	16.20	87

Saft 13 cell stack: I = 3.6A

End V = 11.0 V

NiO₂ cell #28: I = 46 mA

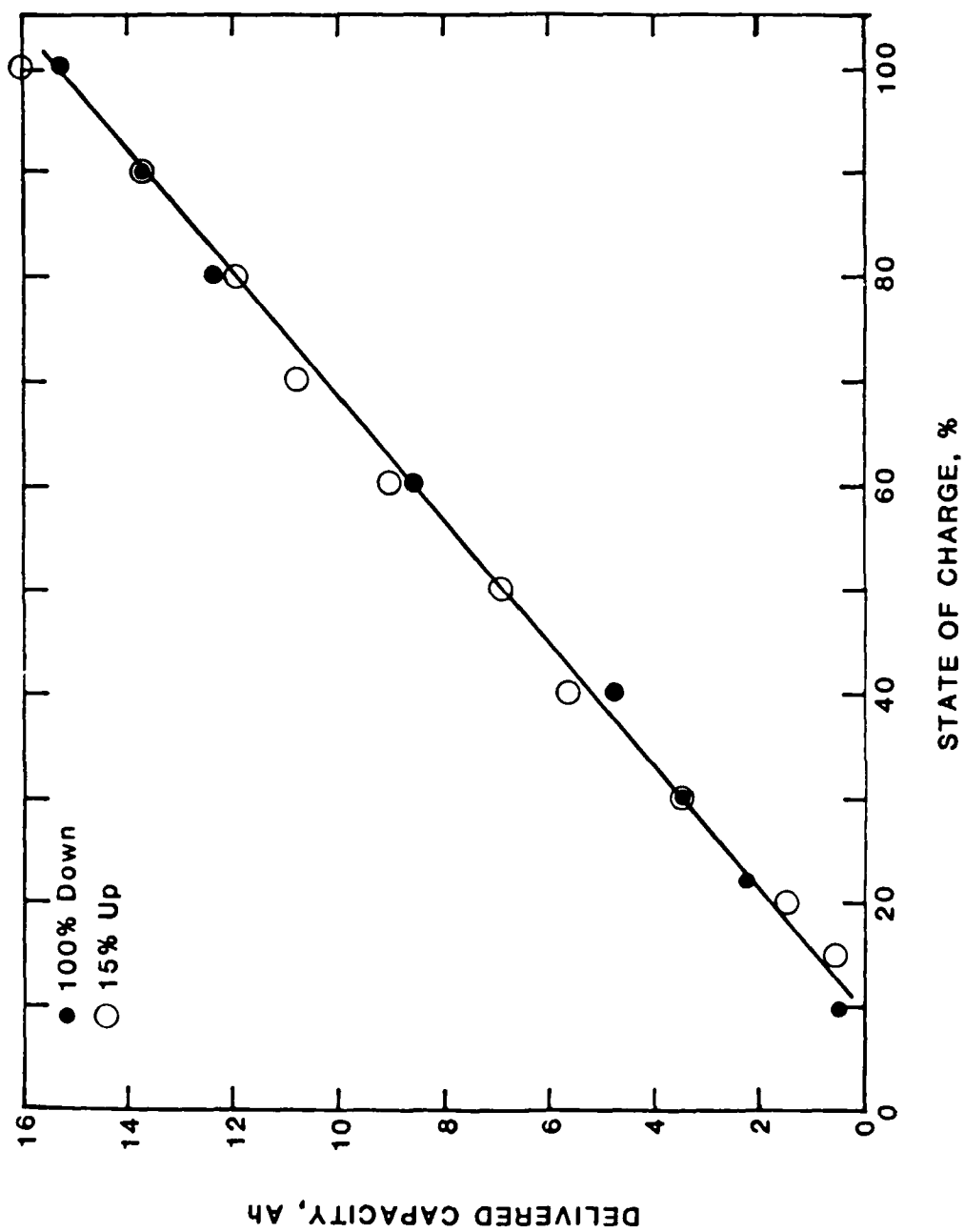


FIGURE 32: STATE OF CHARGE vs. DELIVERED CAPACITY

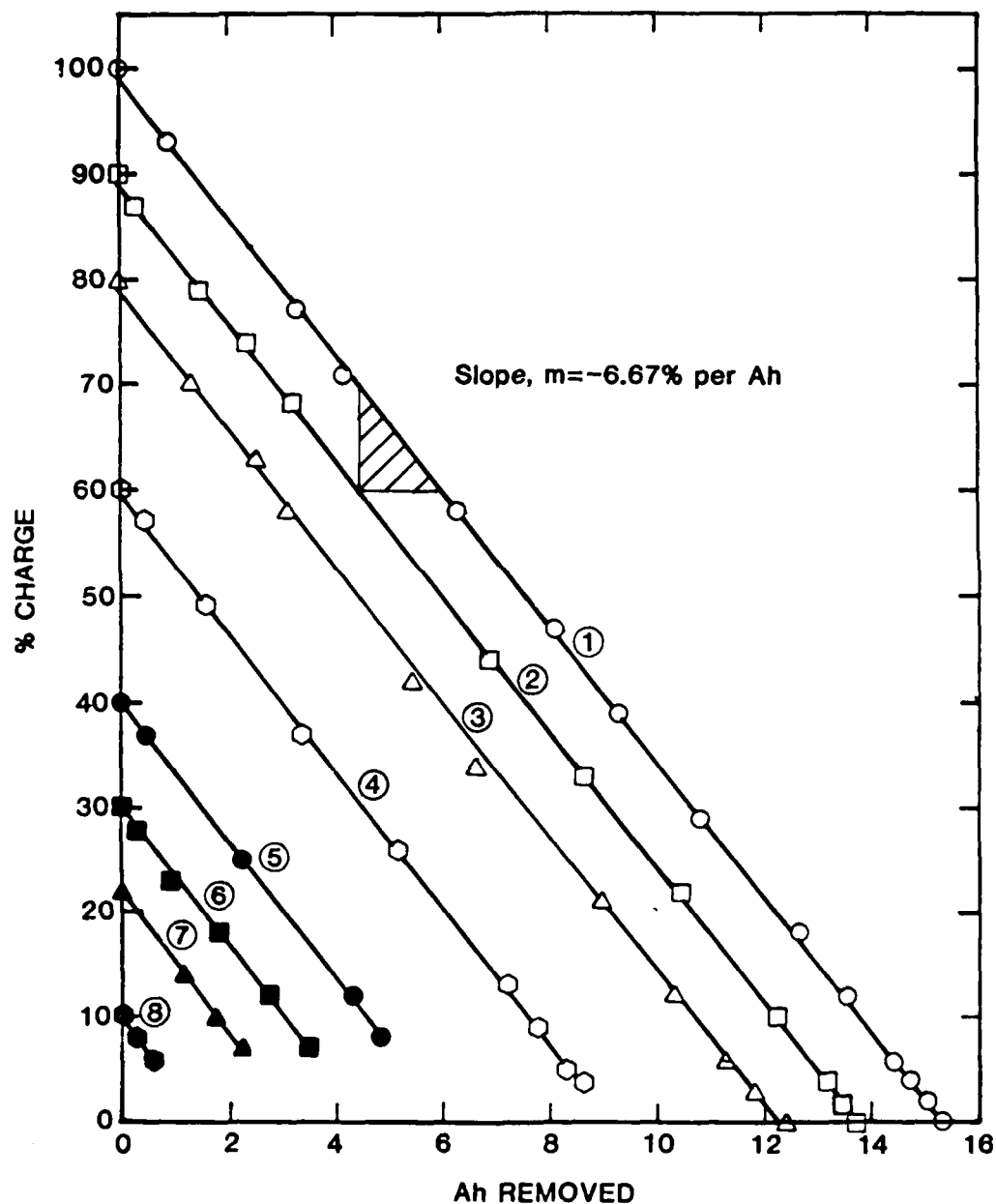


FIGURE 33: CAPACITY vs. STATE OF CHARGE a 100 TO 10%

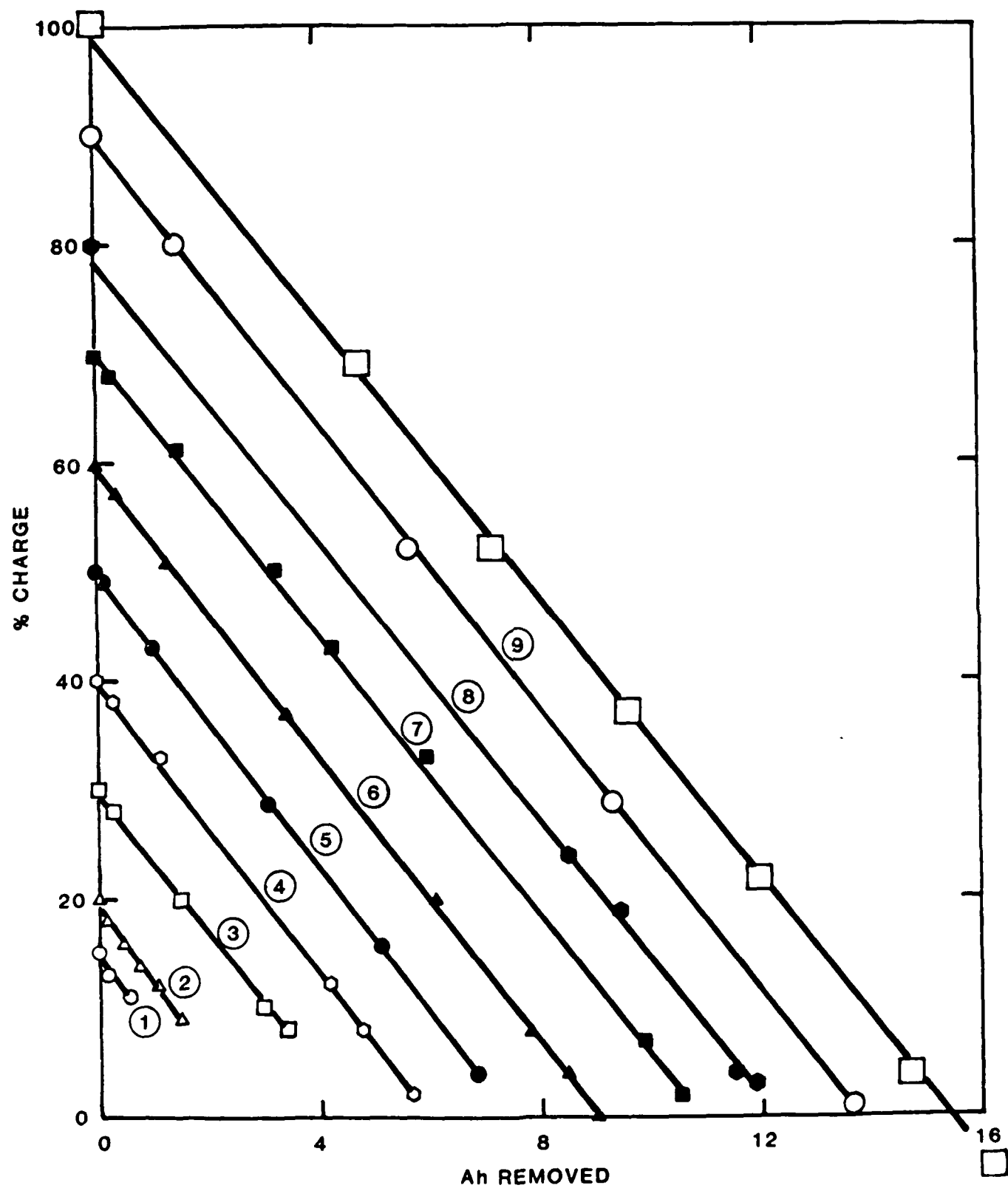


FIGURE 34: CAPACITY vs. STATE OF CHARGE AT 15 TO 100%

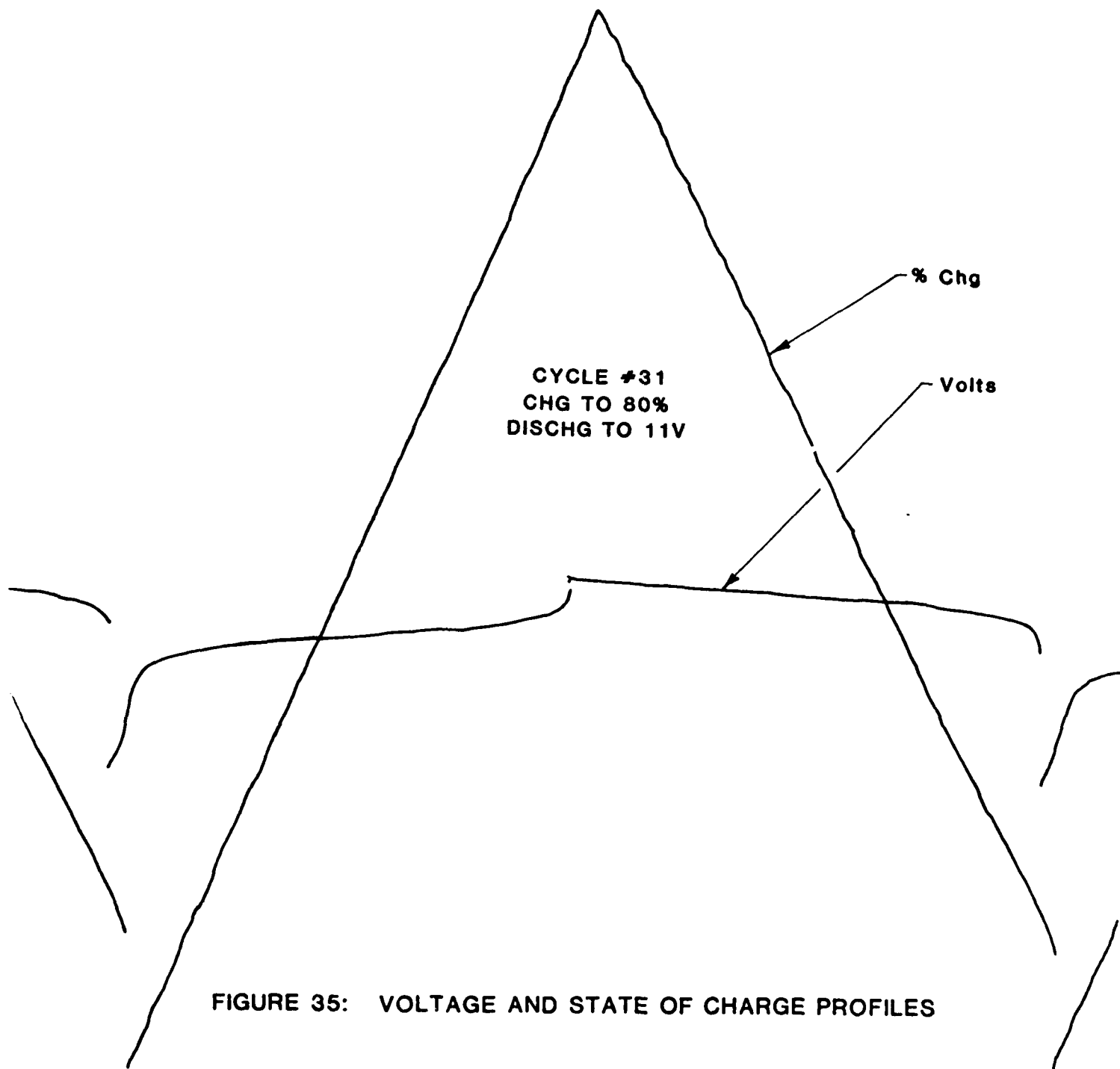


FIGURE 35: VOLTAGE AND STATE OF CHARGE PROFILES

the fuel gauge should indicate the same value of state of charge. However, the fuel gauge reading at the end of discharge did not remain constant.

The system was thoroughly checked and the problem was traced to a defective electronic component which had compounded the normal fluctuations caused by changes in ambient temperature. One more shorted aircraft cell was removed and system was calibrated. The current to the battery was kept the same at 3.5 A and current to the Ni-0₂ cell was increased from 46 to 48 mA. Performance characteristics for Cycle #63 are shown in Figure 36.

As scheduled, after 100 cycles, cycling was interrupted and the test matrix state of charge versus delivered capacity was repeated. The test procedure was as follows: Discharge regime of Cycle #102 was continued for a longer period until the state of charge of the battery reached 0%. The system was charged to 10% and again discharged fully to 0%. This gave the capacity remaining when the battery's state of charge is 10%.

The procedure was repeated increasing the state of charge in steps to 100%, followed by decreasing in steps to 5%. The experimental data are summarized in Table 4.

The test data confirm that the tracking characteristics are both linear and reproducible. Figure 37 shows the

CYCLE # 63
MAIN BATTERY:
SAFT, 12 CELL STACK
PILOT CELL:
Ni-O₂ #28

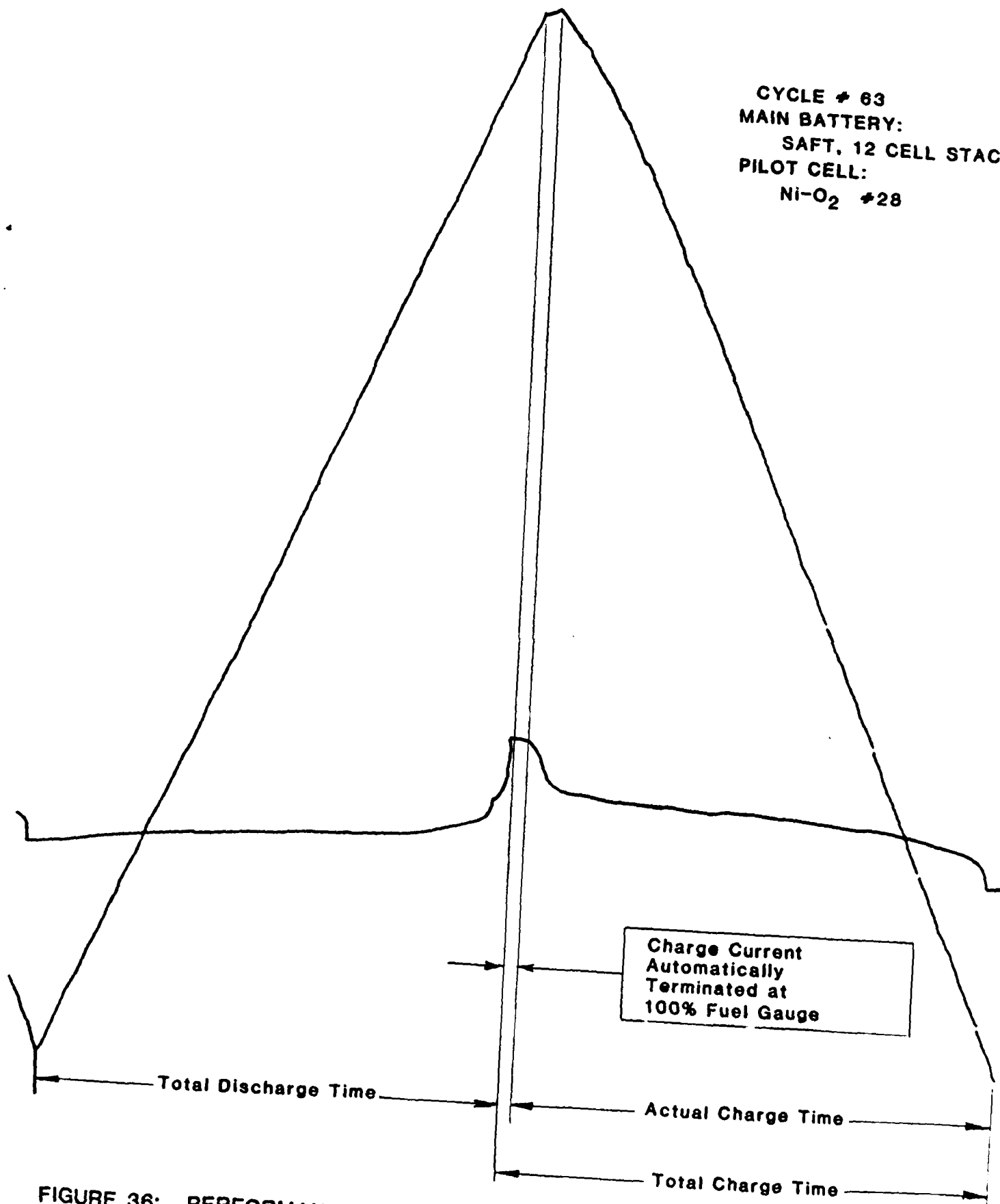


FIGURE 36: PERFORMANCE CHARACTERISTICS OF TRACKING CYCLER-CYCLE 63

TABLE 4
STATE OF CHARGE VS. DELIVERED CAPACITY

CYCLE NO.	CHARGE				DISCHARGE TO 0%		
	END V	HOURS	Ah	%	END V	HOURS	Ah
103	15.94	0.42	1.46	10	12.64	0.42	1.46
104	15.92	0.83	2.92	20	12.50	0.88	3.09
105	16.84	1.47	5.15	40	9.70	1.65	5.78
106	17.02	2.67	9.35	60	12.75	2.52	8.82
107	17.30	3.33	11.66	80	10.00	3.42	11.97
108	19.75	4.67	16.35	100	12.80	4.25	14.88
109	19.95	4.50	15.75	100	13.60	4.25	14.88
110	17.93	4.08	14.28	92	13.93	3.83	13.41
111	17.17	2.83	9.91	70	12.46	3.16	11.06
112	17.04	1.92	6.72	50	6.10	2.16	7.56
113	16.83	1.33	4.66	33	12.00	1.62	5.67
114	16.15	0.43	1.52	10	13.40	0.40	1.40
115	15.80	0.20	0.70	5	13.65	0.20	0.70

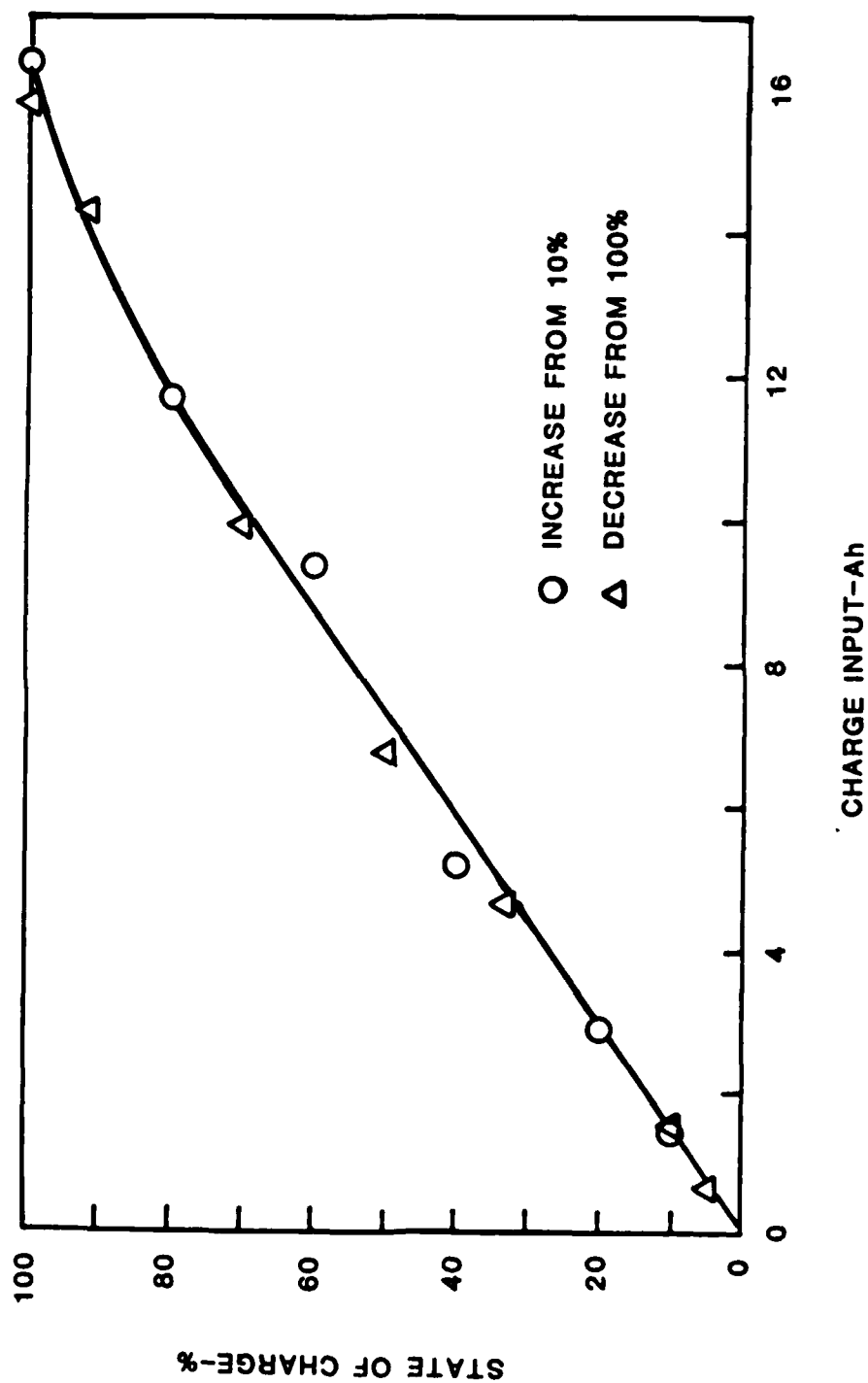


FIGURE 37: CHARGE INPUT vs. STATE OF CHARGE

amount of ampere hour input required to bring the battery's state of charge up from 0%. After a state of charge of about 85% was reached, the linear relationship changed, indicating a leveling off in pressure of the Ni-O₂ cell. The linearity of delivered capacity and state of charge is shown in Figure 38.

After completing this series of tests, tandem operation was resumed on the automatic cycling regimen. Currently the system has been cycled over 400 times and voltages at the end of discharge are lower, indicating loss in capacity. It is proposed to continue cycling with increased overcharge and if improved capacity does not result, the test will be terminated.

The performance characteristics for Cycle #407 are shown in Figure 39, and for cycle 360 in Figure 40. It can readily be seen that the major variation is the drop in the end of discharge voltage from 11.7 to 4.0 volts.

A second cycler, similar to the first, was built to evaluate the tracking characteristics using the aircraft battery made by a second manufacturer (Marathon). As before, a nickel oxygen cell was built with an identical nickel electrode used in Marathon cells. Cycling currents and times were adjusted and the battery was fully charged, followed by a deep discharge and the performance characteristics are shown in Figure 41. Based on the results, further fine tuning of Ni-O₂ cell current was made and cycling was started at ambient conditions. State of charge and voltage profiles for cycle #18 are shown in Figure 42.

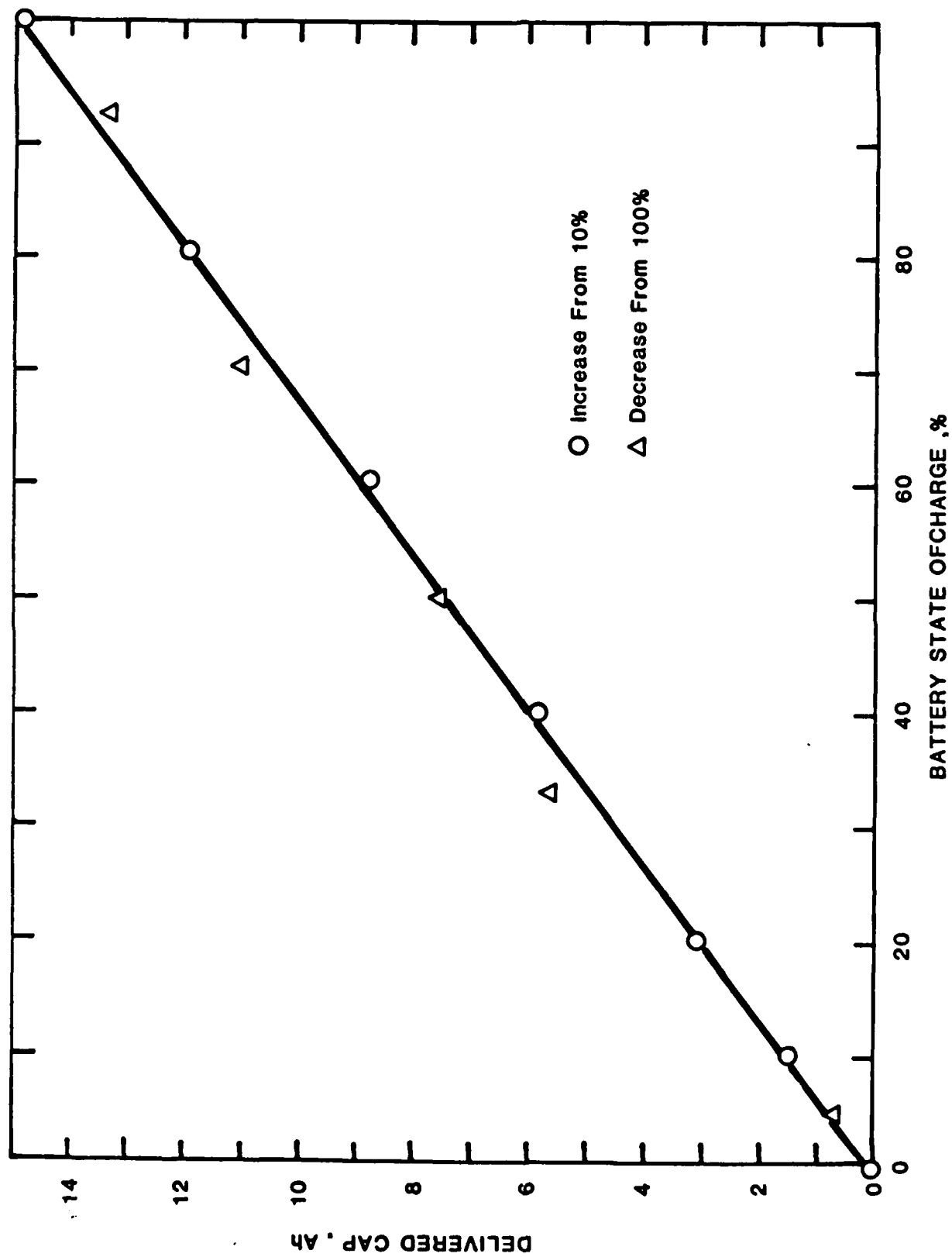


FIGURE 38 STATE OF CHARGE vs. DELIVERED CAPACITY

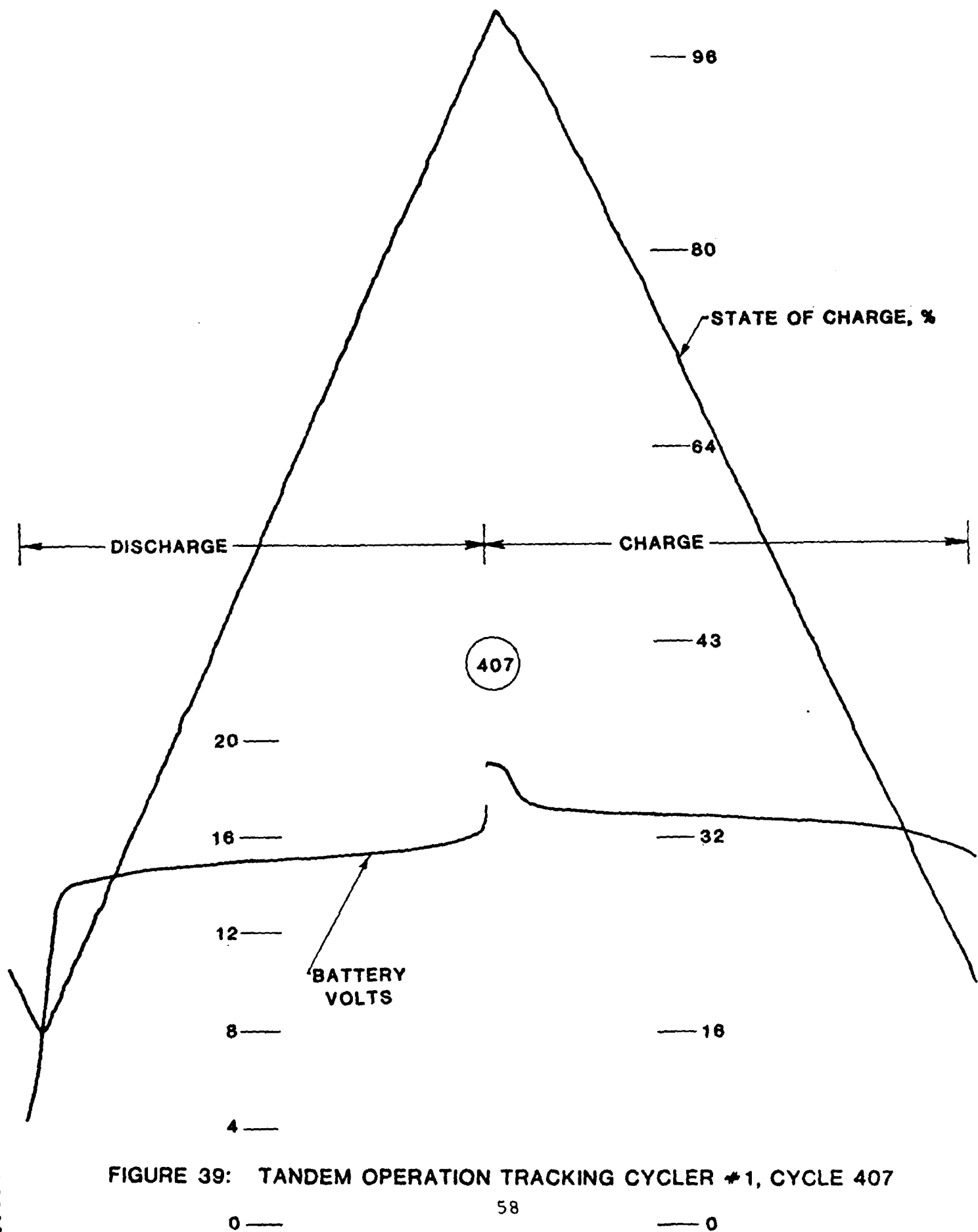


FIGURE 39: TANDEM OPERATION TRACKING CYCLER #1, CYCLE 407

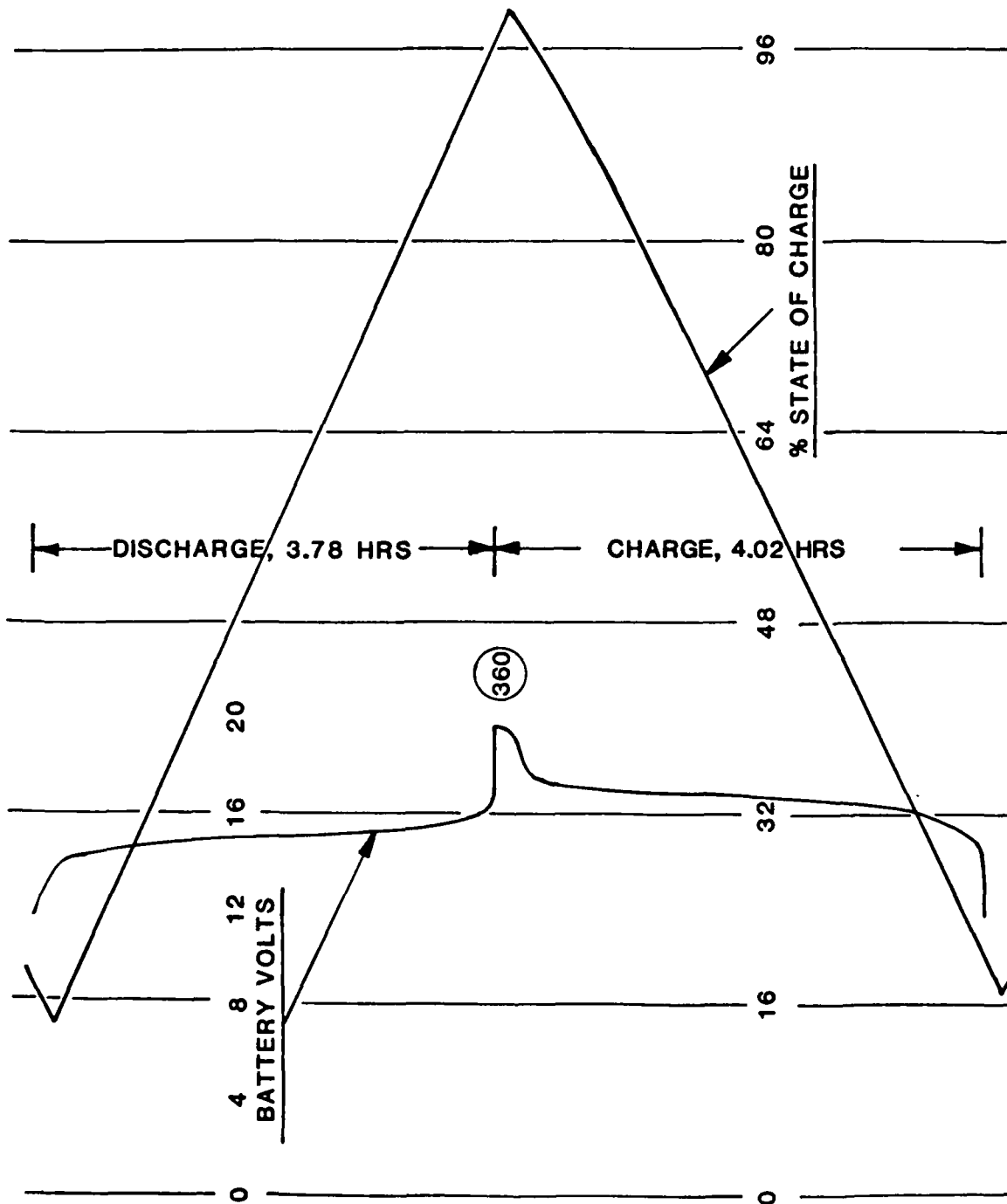


FIGURE 40: TANDEM OPERATION-TRACKING CYCLER #1, CYCLE 360

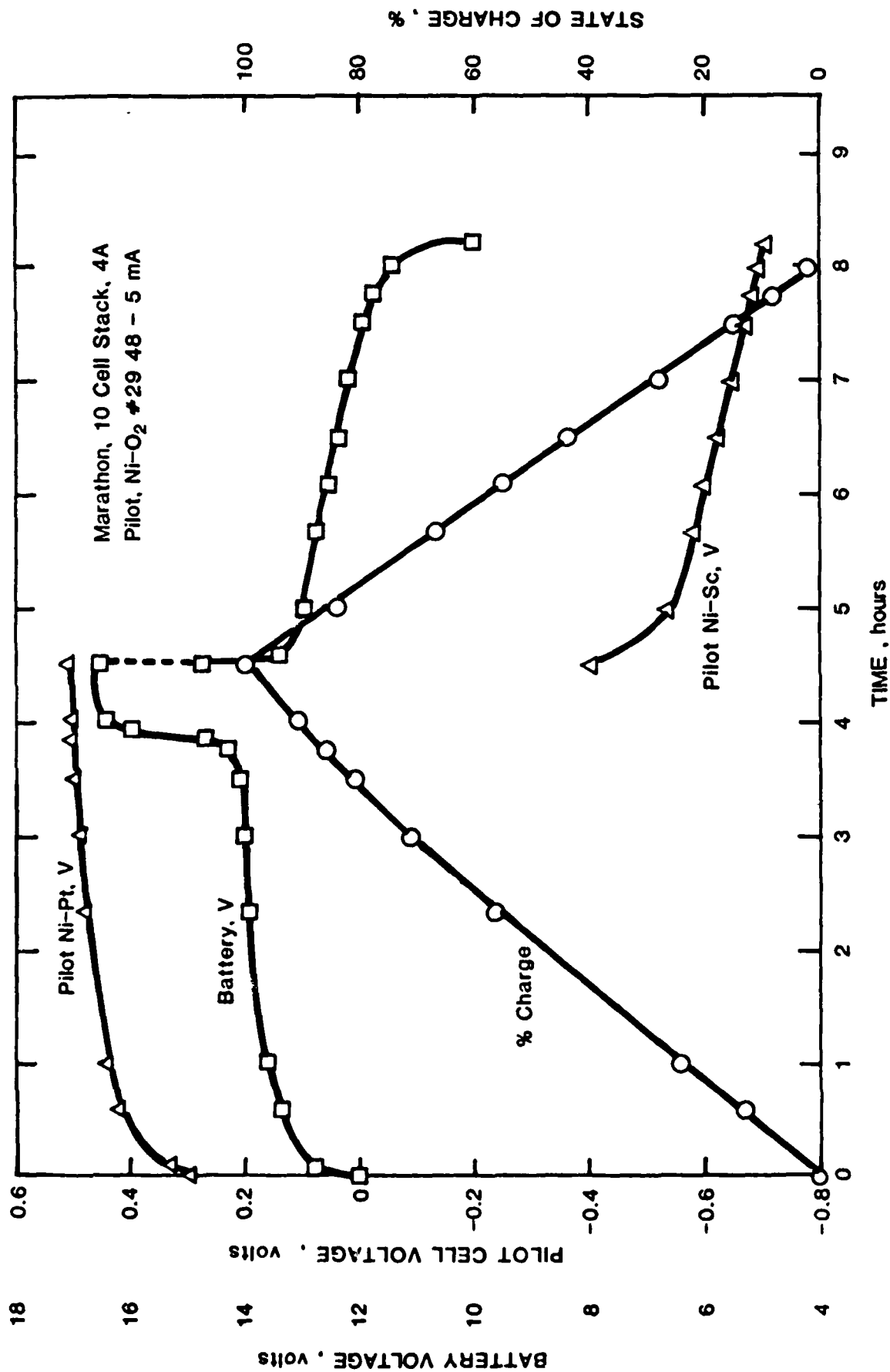


FIGURE 41 TRACKING CYCLOR #2 - 100% D.O.D.

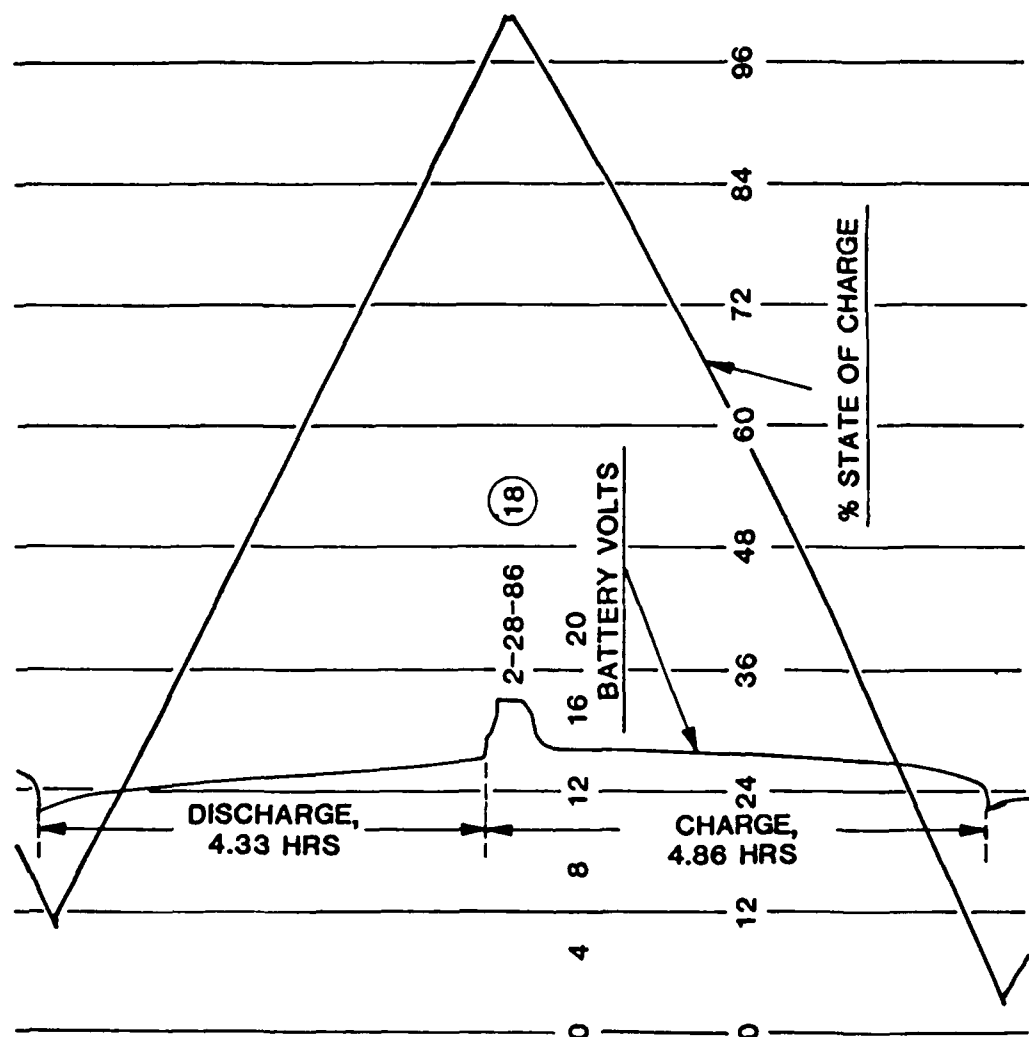


FIGURE 42: PERFORMANCE CHARACTERISTICS-TRACKING CYCLER #2, CYCLE 18

Tandem cycling of this system was performed at a constant temperature of 25°C in order to eliminate fluctuations in pressure of Ni-O₂ cell caused by variations in room temperature. Over 200 cycles have been accomplished and the tracking performance (cycle 195) is shown in Figure 43.

4.0 SUMMARY AND CONCLUSIONS

During the second year, efforts were continued in characterizing the performance of Ni-O₂ cells. The test results confirmed that the performance characteristics of the cells surpass the requirements for tracking the state of charge of commercial aircraft batteries.

Tests to monitor the performance of each working electrode separately proved that eventual cell failure was caused by deterioration of the nickel electrode. Long term life tests have shown that the life of Ni-O₂ cells is well in excess of that of aircraft batteries. In addition, increased polarization of the nickel electrode does not affect the relationship between the state of charge of the nickel electrode and cell pressure.

Efforts during this phase were also directed at proving the system concept. Using an electronics system designed and built in-house, system life and stability were demonstrated. A SAFT aircraft battery was operated in tandem and over 400 cycles were obtained during a 7-month period. The Ni-O₂ cell was still functioning well and tests were terminated due to loss in capacity of the battery.

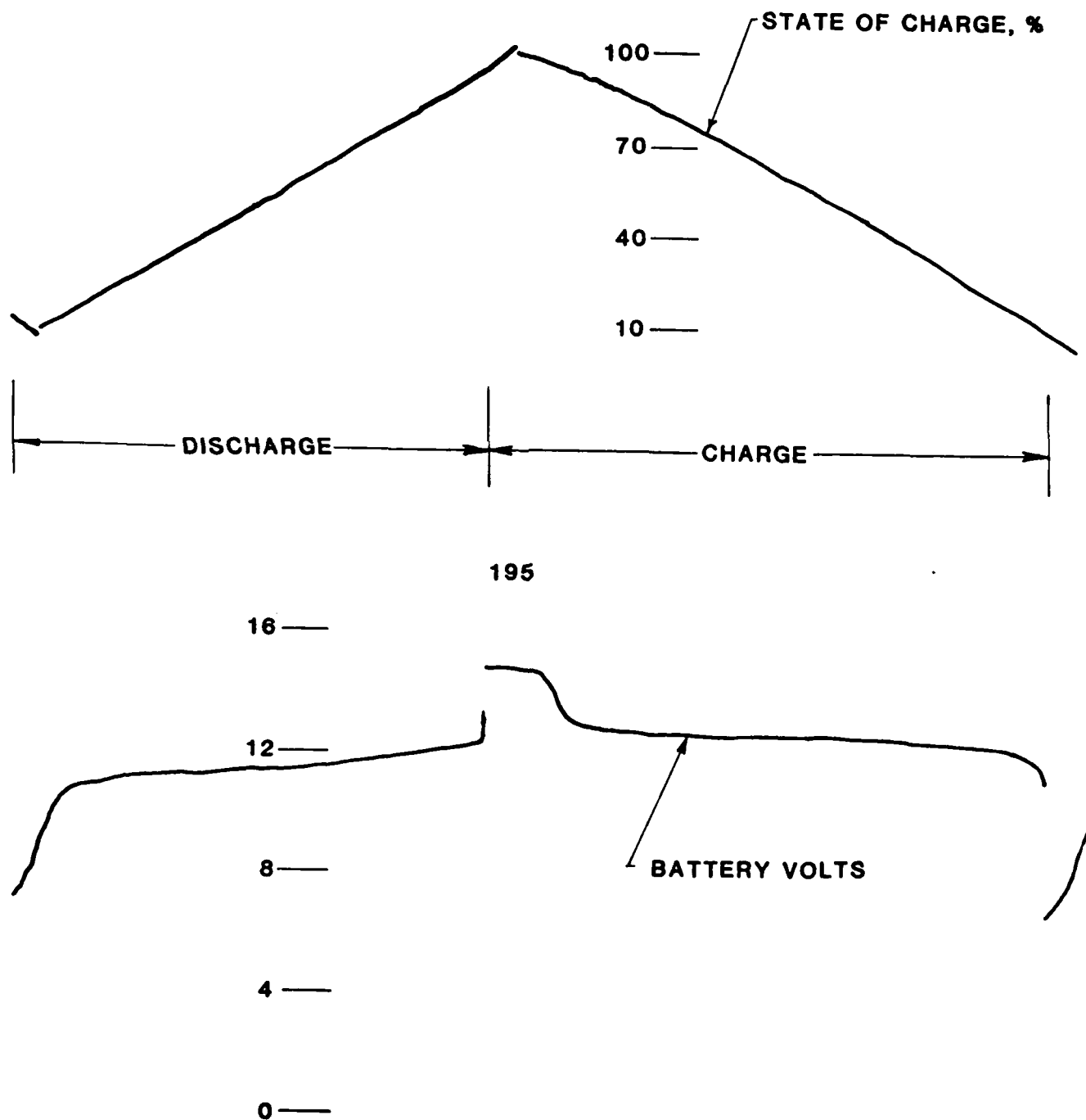


FIGURE 43: TANDEM OPERATION-TRACKING CYCLER #2, CYCLE 195

A second tracking cyclor was built and a Marathon aircraft battery was tested both at ambient and at constant temperatures. Fluctuations in cell pressure and, hence, the percent state of charge caused by variations in temperature were eliminated by keeping the Ni-O₂ cell at constant temperature; accordingly, this resulted in an improved tracking accuracy.

During the next 12 months, efforts will be continued on testing integrated systems at the brass-board level. Tandem operation of Marathon batteries will be performed at constant low temperatures. Two more aircraft batteries-- General Electric and one to be furnished by the Government-- will also be tested as integrated systems using compatible Ni-O₂ cells.

At the conclusion of the next and final phase of this R&D effort, a final report on the work performed under this contract will be delivered along with Ni-O₂ tracking systems.

END

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